Artificial Gravity for Human Exploration Missions

NEXT Status Report

July 16, 2002

B. KENT JOOSTEN
Exploration Analysis and Integration Office
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
2101 NASA Road 1, Houston, TX 77058-3696
Mail Code: EX13 Voice: (281) 483-4645 FAX: (281) 244-7478
kent.joosten@jsc.nasa.gov

Study Contributors

- GRC – Trajectory Analysis, Propulsion
- LaRC – Structural Analysis
- MSFC – Consultation - Propulsion, Power, Tether
- JPL - Propulsion
- JSC – Trajectory Analysis, Dynamics Analysis, Habitation Systems, Power/Propulsion Design, Vehicle Layout

Agenda

- <u>Introduction</u>
- Study Results to Date
  - Trajectory Analysis
  - Dynamics
  - Structures
  - Power, Propulsion
  - Habitation
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Study Objectives, Constraints, Approach

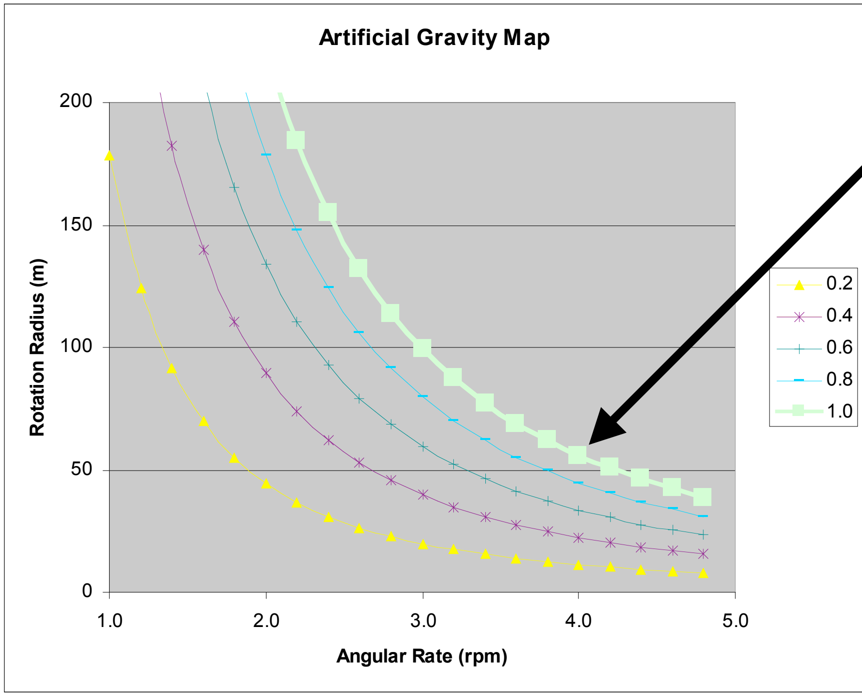
- **Objective:**
  - Demonstrate preliminary engineering feasibility of artificial-gravity (AG), interplanetary human exploration spacecraft
  - Identify positive or negative system and mission impacts related to AG requirement
- **Constraints:**
  - Artificial-gravity levels and rotational parameters as agreed to by NASA NEXT team March 2002
- **Approach:**
  - Choose "archetype" mission to drive out system performance requirements
  - Make spacecraft systems selections with greatest AG synergy

Rationale for Artificial-G

- **Continuing *serious* concerns regarding human physiological effects of long-duration microgravity exposure**
  - **Loss of bone mineral density**
  - **Skeletal muscle atrophy**
  - **Orthostatic hypertension**
- ***Current countermeasures deemed ineffective* (in particular w.r.t. bone mineral density loss)**

AG Constraints

- **Nominal design = 1.0 g**
  - **Essentially no data on efficacy of hypo-g as countermeasure**
  - **Acquiring this data would likely be difficult, time-consuming, and expensive**
- **Rotation levels ! 4 rpm**
  - **Acceptable crew adaptation times based on rotating room studies**
- **Implies rotation radius of " 56 meters**



Design Goal

Mission Archetype

- Intent is to make vehicle concept destination-independent
- However, Mars round-trip "opposition"missions (all opportunities) chosen as study archetypes
  - Characteristics
    - 18-24 month round trip (18 month goal)
    - Three months stay in Mars system
    - "Split mission" – no "Mars-specific" cargo sent out with crew
    - Departure/return point: Earth-Moon L_1
    - Destination: Mars-Sun L_1 or high Mars orbit
    - Less than 200 tons initial mass
  - Rationale
    - Stresses interplanetary "steering" requirements (possible AG concern)
    - Stresses inner solar system operating regime (0.5-1.5 AU)
    - Stresses propulsion performance
    - Out of 18-24 month round trip, three months Mars stay with *no gravity readaptation time required* may represent good mission productivity
    - "Split mission" maintains destination-independence of crew transfer vehicle
    - Earth-Moon L_1 staging consistent with "Earth's Neighborhood" infrastructure; may be consistent with nuclear system operation
    - Mars L_1 avoids mission-specific orbital operations and requirements
      - Implications of lower orbit access will be addressed

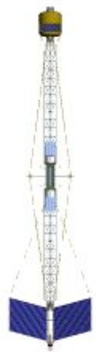
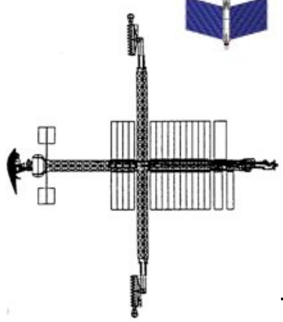
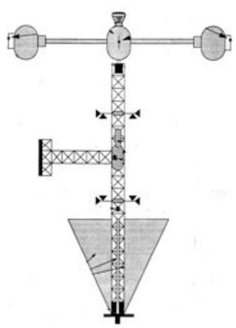
Technology/Systems Selections

- Nuclear Electric Propulsion - NEP and artificial gravity may be good match in vehicle design (NEXT Groundrule)
  - Constant low-thrust
    - Allows thrusting while under spin (low forces, torques)
      - No spin-down, burn, spin-up sequences
    - Steering techniques required
  - Vehicle configuration compatibilities
    - Long booms, trusses, etc. required for AG moment arms can serve as reactor "$1/r^2$" crew radiation shielding
    - Reactor, power conversion systems = good "counterweight"
- ECLSS – Regenerable water, oxygen
  - Mission times consistent with AG require closed systems
  - Lower mass system choices possible if high power availability assumed (consistent with NEP)
- Other system choices were assessed as to influence of 1-g operation

Other Assumptions

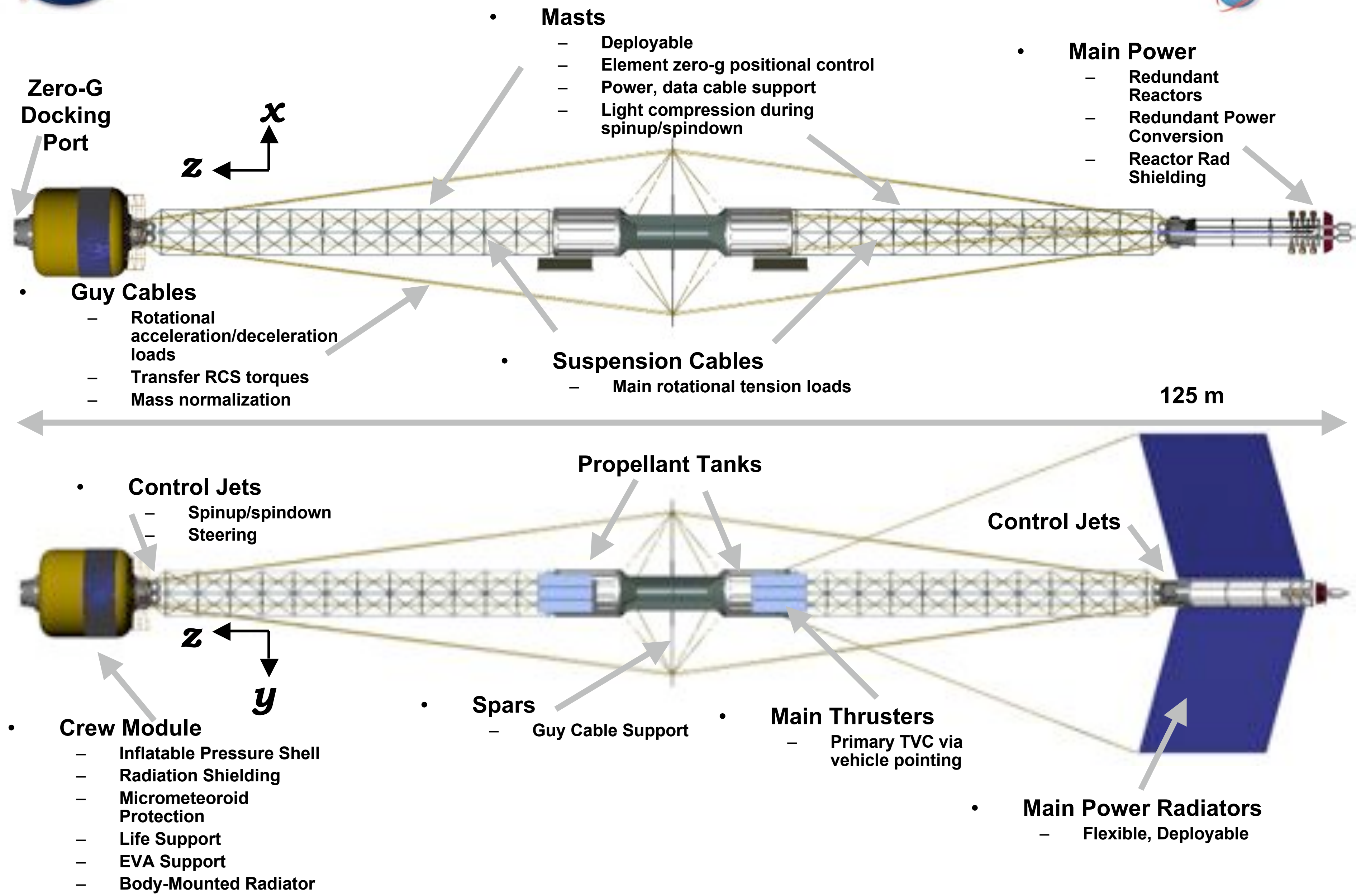
- Technology Horizon ~ 2015
  - Avoid conclusions regarding AG feasibility being influenced by questionably optimistic technology assumptions
  - Implications for NEP (validated by MSFC)
    - Isp: 4000 – 6000 sec
    - Power: 5 – 12 MWe
    - Specific Power (#): 4 – 8 kg/kWe
- Reusability " 3 missions
  - AG vehicle configurations may require substantial on-orbit assembly/outfitting
    - High overhead if required for every flight
  - Nuclear systems will represent substantial investment
  - Consistent with high energy density potential of nuclear systems

Potential AG Configurations

Concept	Features	Potential Advantages	Potential Challenges
"Fire Baton" 	•Hab counterweighted by reactor/power conversion systems •Entire vehicle rotates •Vehicle pointing provides majority of thrust vector control (TVC)	*•No rotating joints, power connections, fluid connections, etc.* •Power conversion systems operate in g-"field"	*•Vehicle angular momentum must be continuously vectored for TVC* •Thermal radiators in g-"field" •Crew ingress/egress
"Ox Cart" 	•Hab counterweighted by reactor/power conversion systems •Thrusters, despun, gimbaled for TVC	*•Thrust vectoring decoupled from rotational angular momentum* •Power conversion systems operate in g-"field"	*•Megawatt-level power , prop transfer across rotating joints* •Potential cyclical loading of rotating joints •Thermal radiators in g-"field" •Crew ingress/egress
"Beanie Cap" 	•Split habitation volumes for counterweights •Reactor/power conversion systems, thrusters in zero-g •Thrusters gimbaled for TVC	*•Thrust vectoring decoupled from rotational angular momentum* •Thermal radiators in zero-g	*•Inefficiencies in duplicating habitation systems, crew transfer between them* •Potential cyclical loading of rotating joints •Power conversion systems operate in zero-g *•Kilowatt-level power transmission across rotating joints*

- **Study Strategy**
  - Address challenges of first configuration (probably simplest to understand)
  - If successful, defer analysis of other options for more in-depth study of option 1
  - Identify findings common to multiple configurations

Current Configuration



Agenda

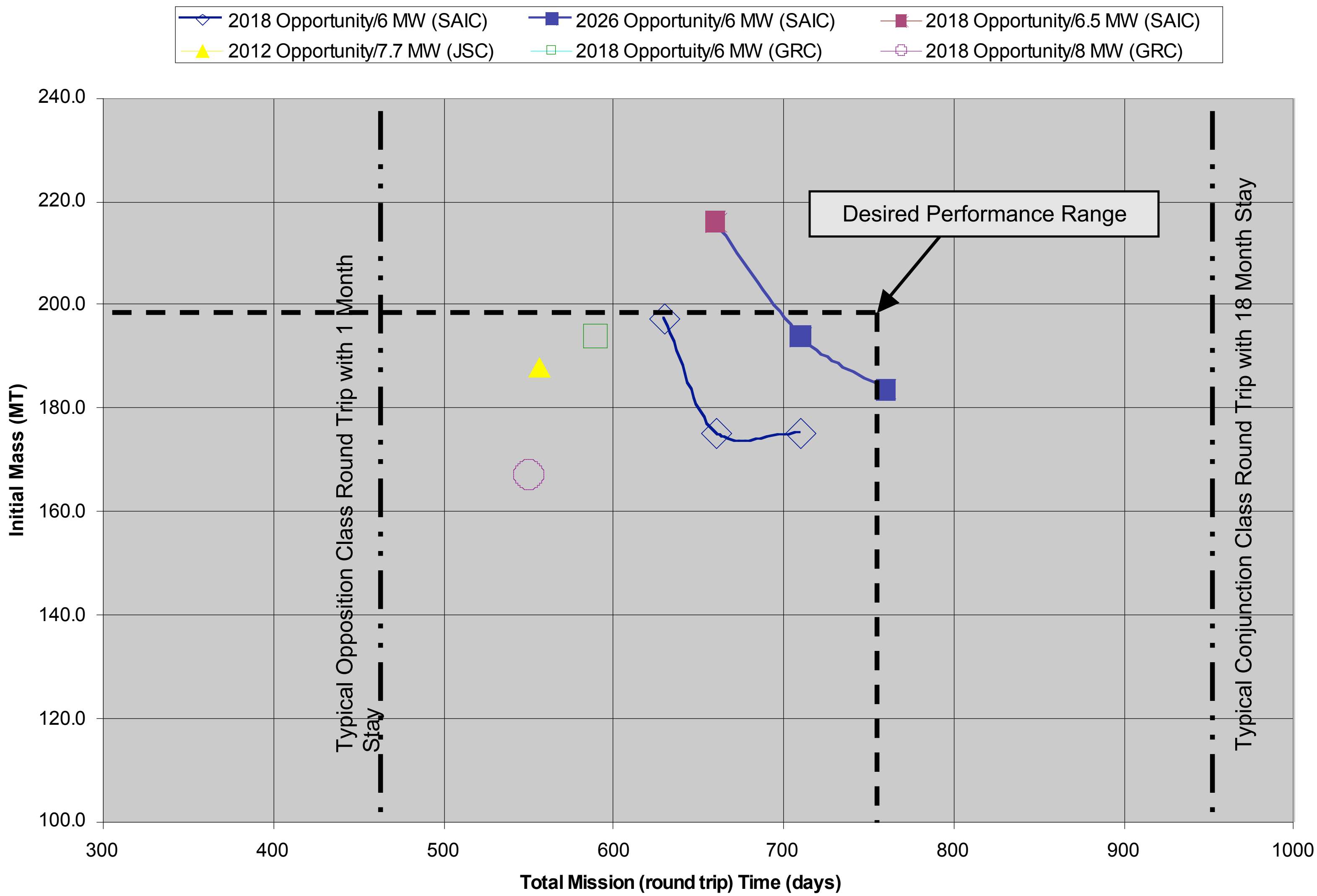
- Introduction
- <u>Study Results to Date</u>
  - <u>Trajectory Analysis</u>
  - Dynamics
  - Structures
  - Power, Propulsion
  - Habitation
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Trajectory Analysis

- Approach
  - Look at performance in representative good opportunities (2018) and poor opportunities (2012 or 2026)
  - Systematically vary key parameters to gauge general performance
    - Isp
    - Power and α
    - Flight time
  - Plot initial mass as a function of these parameters
- Three different groups supporting the trajectory analysis activity:
  - JSC/EG using the RAPTOR tool, based on calculus of variations with a genetic algorithm to find a reasonable initial point
  - GRC using the VARITOP tool, based on calculation of variations
  - SAIC/Chicago using CHEBYTOP tool, based on Chebyshev polynomial approximations
- Results being compared to understand both trajectory characteristics and any biases introduced by tool characteristics.

Initial Mass Performance

(as a function of total flight time)



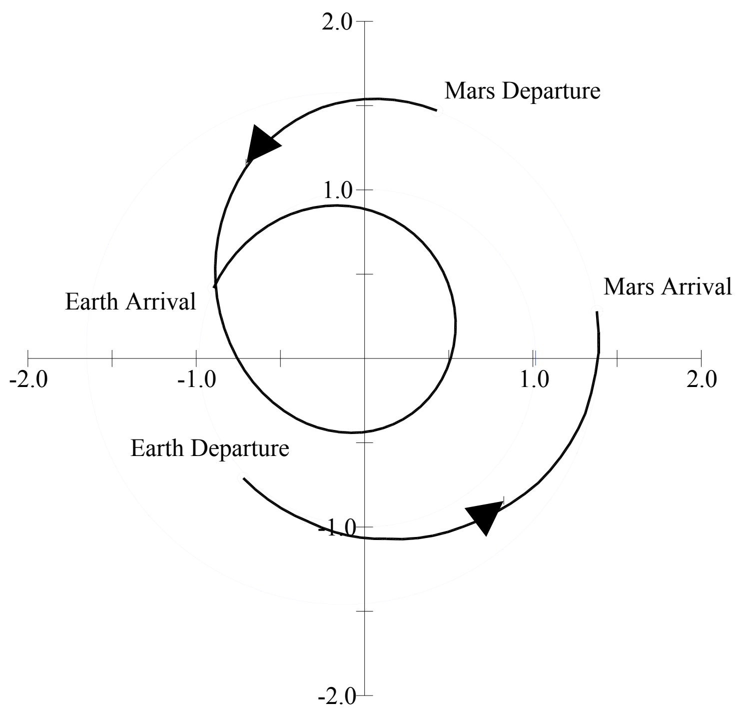
Example Trajectories

2018 Opportunity

660 Day Round Trip Case

(Favorable Opportunity)

Perihelion = 0.426 A.U.

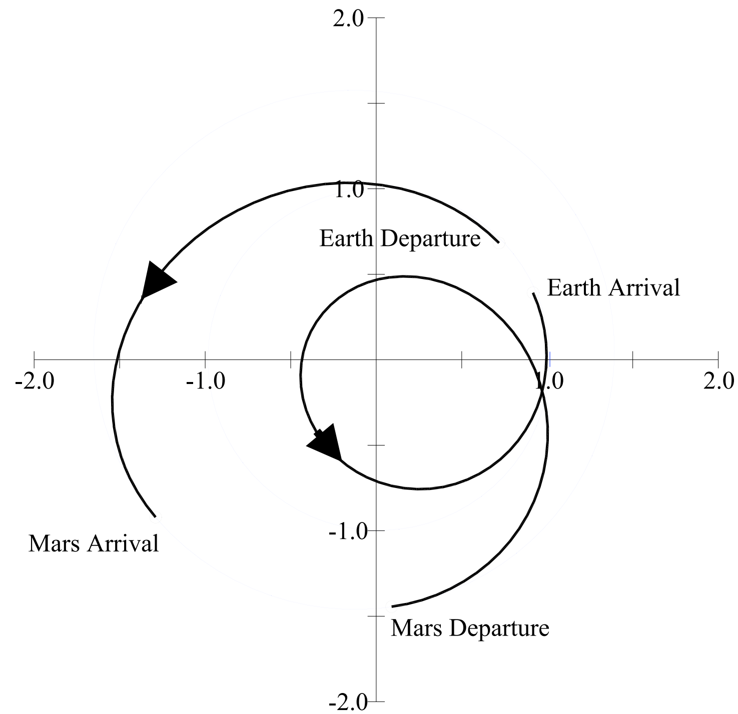


2026 Opportunity

710 Day Round Trip Case

(Unfavorable Opportunity)

Perihelion = 0.416 A.U.



For both cases: 6MW at 6 kg/kW, 5000 sec Isp, 90 MT dry mass

Trajectory Analysis Observations (so far)

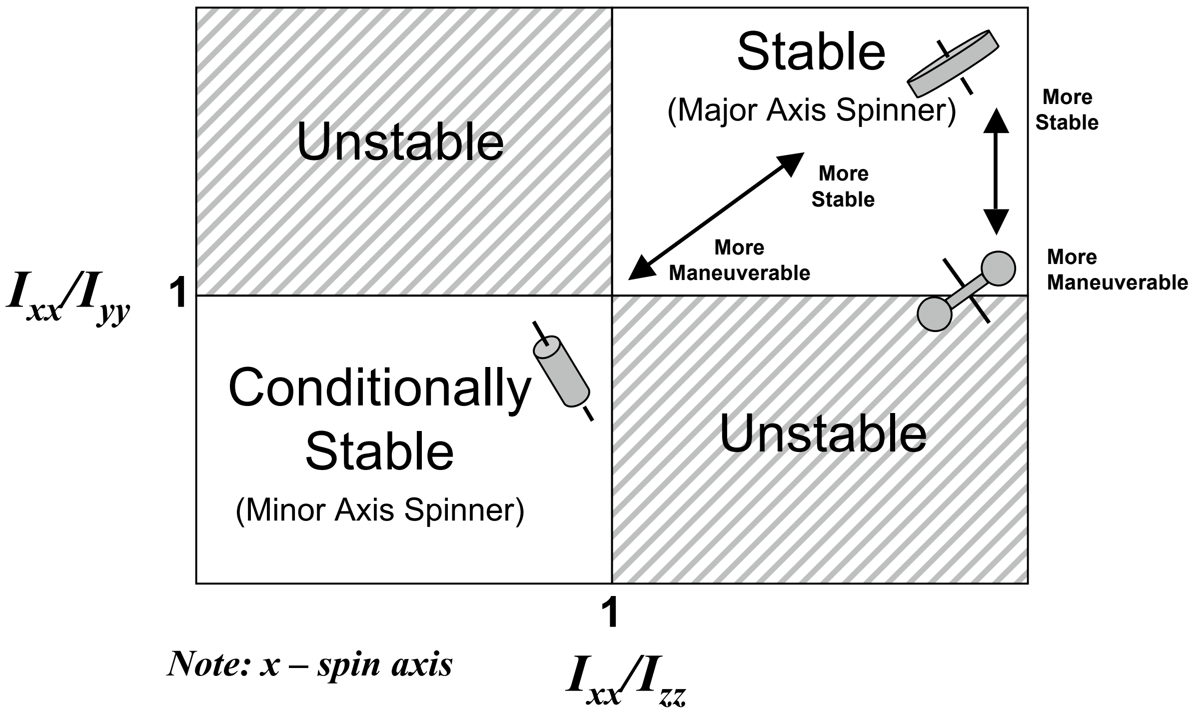
- **Mission can be accomplished for initial total mass and reactor power targets for all opportunities.**
  - Flight times are at upper end of goals
  - Shorter flight times are achievable
    - Higher power level
      - Implies more challenging power system α's (to maintain desired habitat counterweight)
    - Additional trajectory "tweaking"
      - Additional thrust arc on return leg
      - Venus gravity assist
- **Return leg perihelion**
  - Higher heating rates (habitat TCS shows acceptable)
  - Higher radiation level if an SPE is encountered (TBA)
  - May be somewhat alleviated by trajectory tweaks

Agenda

- Introduction
- <u>Study Results to Date</u>
  - Trajectory Analysis
  - <u>Dynamics</u>
  - Structures
  - Power, Propulsion
  - Habitation
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Spin Stability

Ratios of Moments of Inertia determine spin stability about corresponding axes

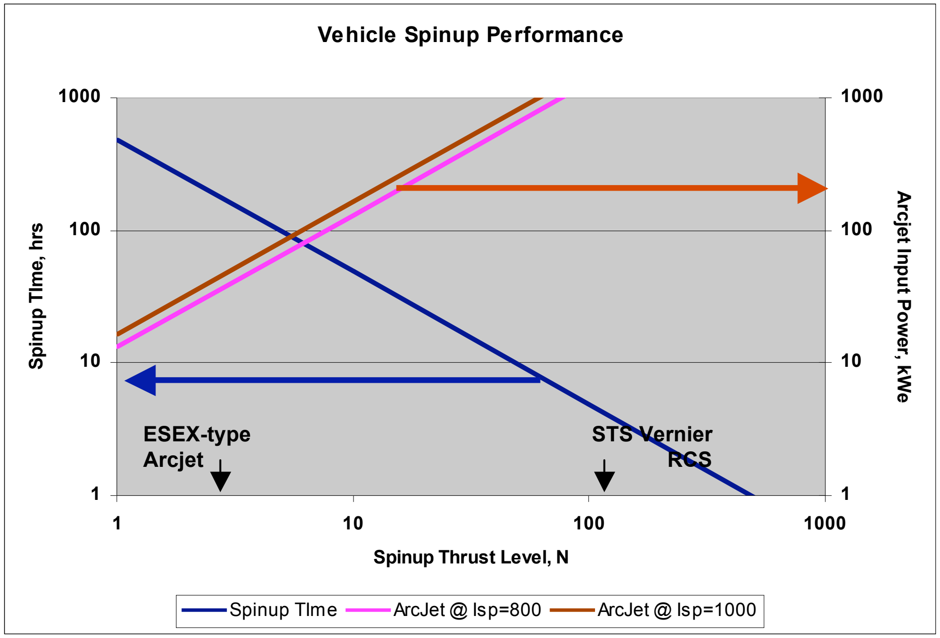


Note: x – spin axis

Spinup / Spindown

- Vehicle spinup/spindown requirements not difficult to meet
  - Large moment arm for RCS
  - Trade between thrust level and thruster on-time
- Arcjet RCS may have role to play if:
  - Robust vehicle power available
  - Propellant reduction a priority
  - Improvement in arcjet thruster throughput
  - Extended (days) spinup time OK
- Flywheel momentum storage probably not a player
  - Momentum storage = 1 m dia., 55,000 kg flywheel at 60,000 rpm

Thruster Isp, sec	Prop mass for spinup (or down), kg
310 (MMH/N2O4)	580
450 (LOX/LH2)	400
800 (Arcjet)	222
1000 (Advanced Arcjet)	180



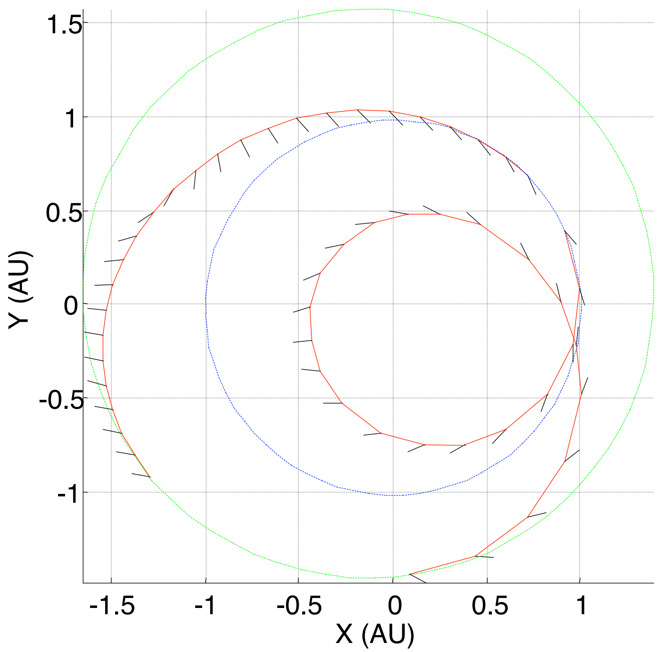
Total moment = 2*Thrust*Moment arm

Moment arm = 50 m

Vehicle I_{xx} =2.1x10^8 kg-m^2

Steering Requirements

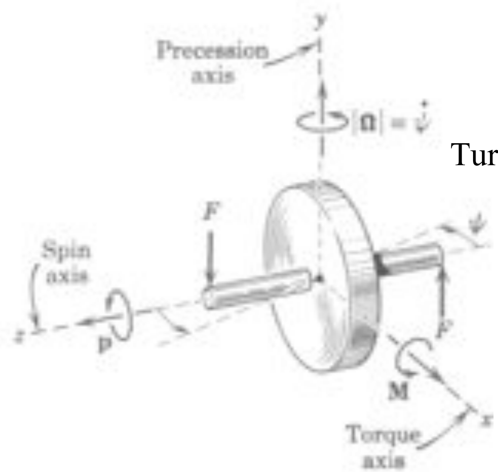
2026 Opportunity – 710 day Total Mission



Mission Phase	Maximum Turn Required	Maximum Required Turning Rate
Earth-Moon L_1 Departure/Arrival	2 x 90°-180°	13°/day
Heliocentric	580°	2°/day
Mars-Sun L_1 Arrival/Departure	180°	2°/day
Mid-Course Thrust Reversal	2 x 180°	~10 °/day

- **Steering requirements seem to fall into two classes**
  - **Very slow rates during majority of trajectory (interplanetary cruise)**
  - **Moderate rates during Earth departure/arrival and mid-course**
- **Different steering strategies may be pursued for these classes**
- **Higher rates not anticipated unless mission requirements change (descent to lower Earth/Mars orbits)**

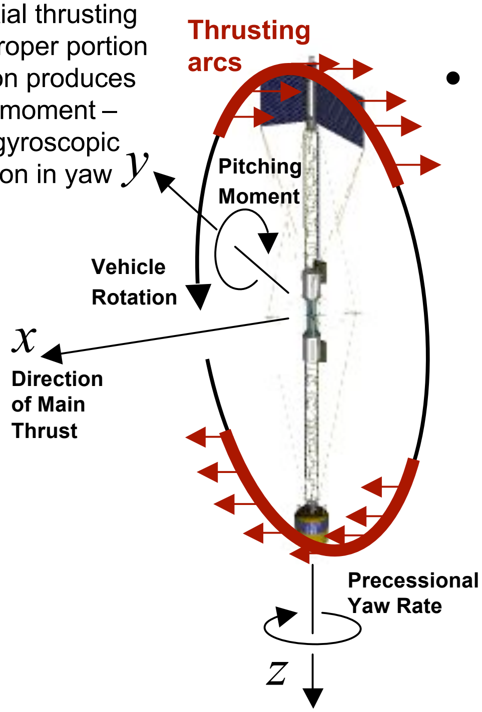
Gyroscopic Precession



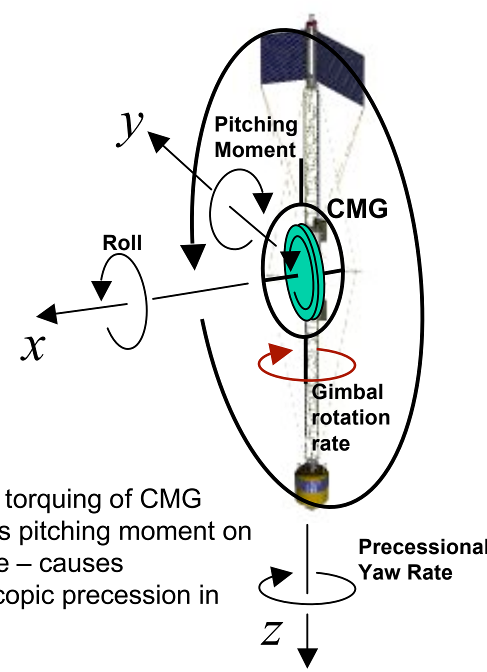
$$\text{Turn rate: } \quad \Omega = \frac{2Fr}{I_P p}$$

- **Precession (steering) accomplished by torquing at right angles to desired rotation direction**
- **Constant torque produces constant steering rate**

Differential thrusting during proper portion of rotation produces pitching moment – causes gyroscopic precession in yaw

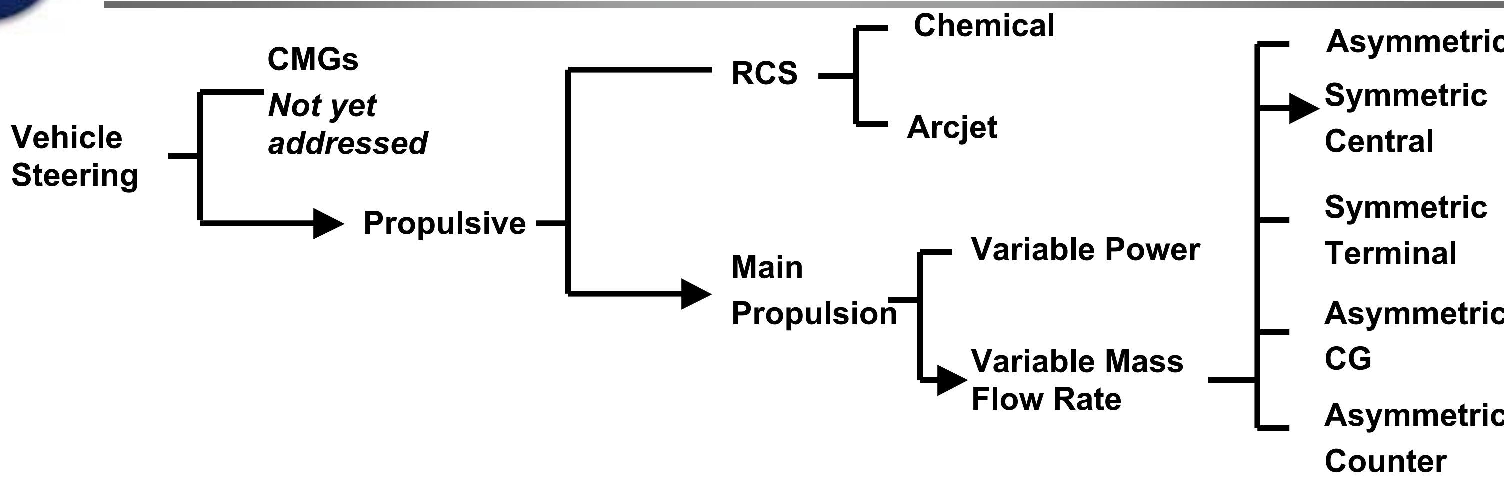


- **Two methods of torquing rotating vehicle under examination**
  - **Differential thrusting during appropriate rotation arcs**
  - **Control Moment Gyro torquing of spacecraft by commanding gimbal rates**

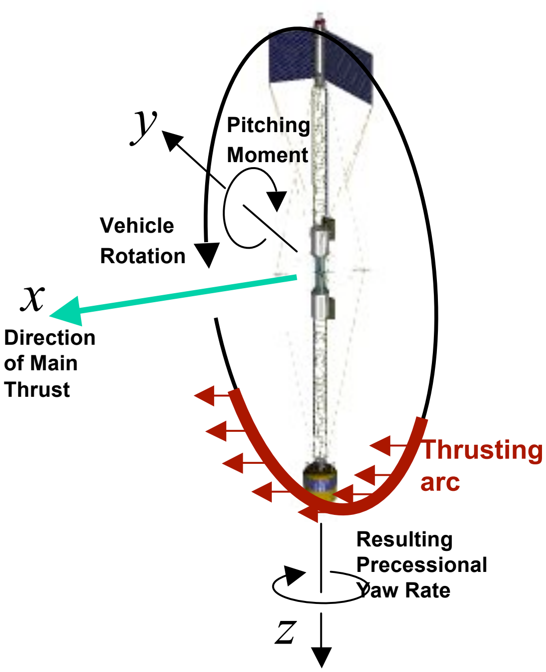


Cyclic torquing of CMG causes pitching moment on vehicle – causes gyroscopic precession in yaw

Steering Trades

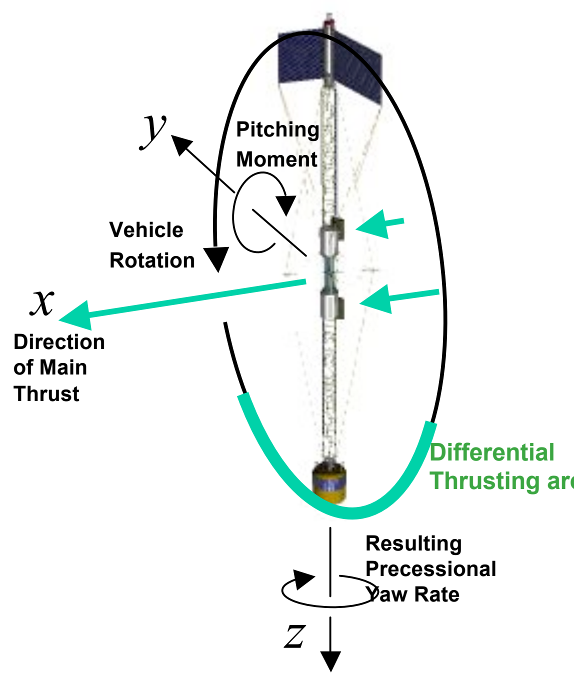


Steering with RCS



- If steering with RCS, thrusting would occur in +x direction only
  - Augments main propulsion
  - Thrusters could be utilized at either or both ends of vehicle
- If steering with main propulsion, thruster(s) would be differentially throttled at appropriate time during rotation

Steering with main(s)



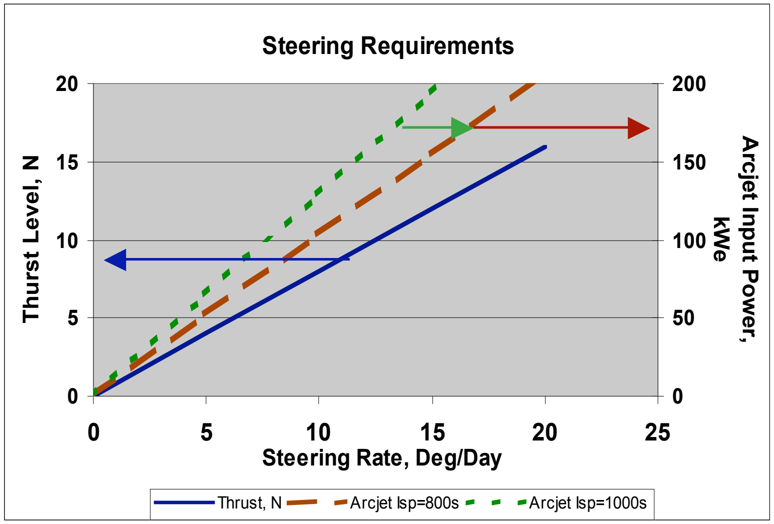
RCS Precessional Steering

- **Propellant Quantities**
  - Effectiveness of RCS steering can be estimated by integrating precession eq.
  - Prop quantities relatively high for chemical systems – could total 10-15 tons if all turning done with precessional RCS (assuming 4x360°)
  - Quantities can increase up to 35% if rotational thrusting arcs are long (inefficient moment generation)
- **Thrust Levels**
  - Thrust levels required for vehicle turning computed from precession eq.
  - "Thrust Profile Factor" used to account for thrust pulse characteristics (*f*)
- **Arcjets may be applicable**
  - Propellant quantities reasonable (4-5 tons for 4x360°)
  - Power available
  - For "high" turn rates (15°/day), 10-15 N thrust, 100-150 kWe
  - For low turn rates (2°/day), 2-3 N thrust, 20-30 kWe
  - If higher thrust & power used throughout: 500 hrs total burn time, 500,000 cycles (18 mo. continuous)
- **Propellant quantities probably excessive for chemical thrusters**

$$\Delta\psi = \frac{g I_{sp} m_{prop} r}{I_{xx}\omega_S}$$

RCS Isp, sec	Prop. for 360° yaw, kg	Normalized for main prop. savings, kg.
310	4000	3690
450	2760	2450
800	1550	1240
1000	1240	930

$$\dot{\psi} = f\,\frac{r\,T_a}{I_{xx}\omega_S}$$

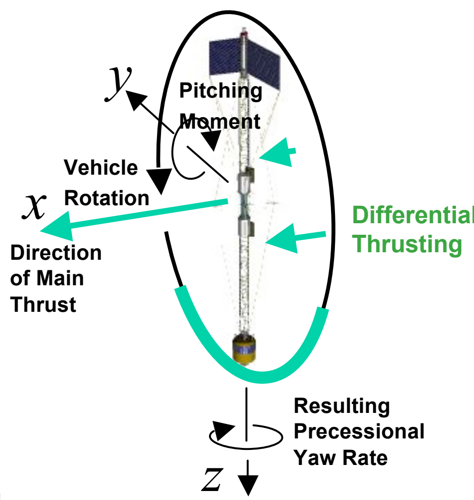


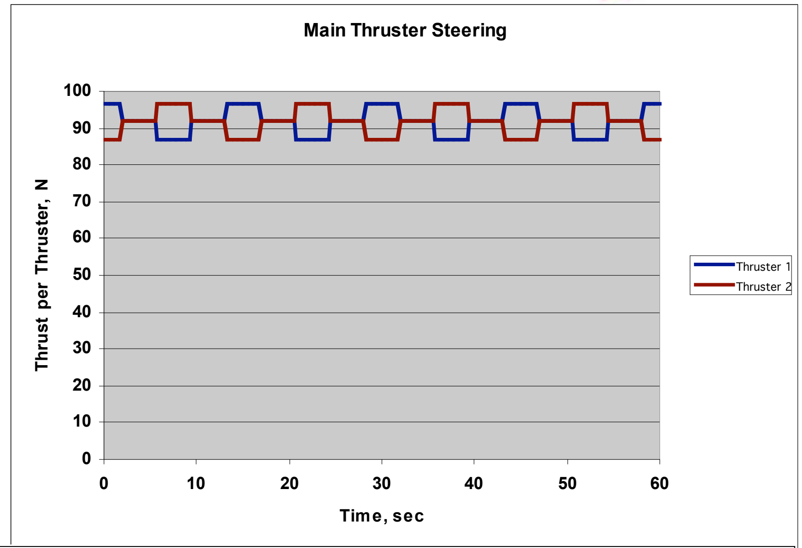
Moment arm = 50 m
Pulse applied every 180°
Pulse "Width" = 90° of arc (90% thrusting efficiency)
Arcjet Eff. = 30%
Vehicle I_{xx} =2.1x10^{8} kg-m^{2}

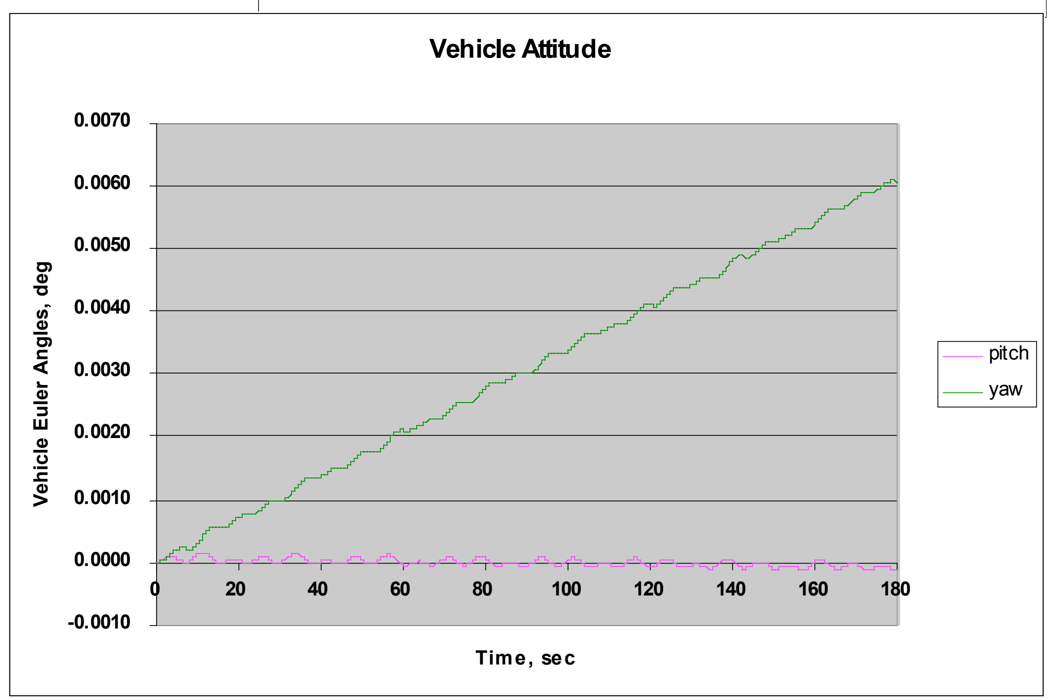
Main Propulsion Steering

- **Moments generated by differentially "throttling" EP thrusters. Can be accomplished by:**
  - **Varying propellant flow rate at constant power (approach selected)**
  - **Varying power at constant flow rate**
  - **Additional main propulsion analysis to determine best approach**
- **Thruster location will determine moment generated by given throttle profile**
  - **"Symmetric central" chosen for minimal propellant line length**
- **Selected performance:**
  - **±5% Thrust (±5 N) per thruster**
  - **Produced by ±0.25 g/sec prop flow rate**
  - **Results in 2.5°/day turn rate (sufficient for interplanetary cruise)**

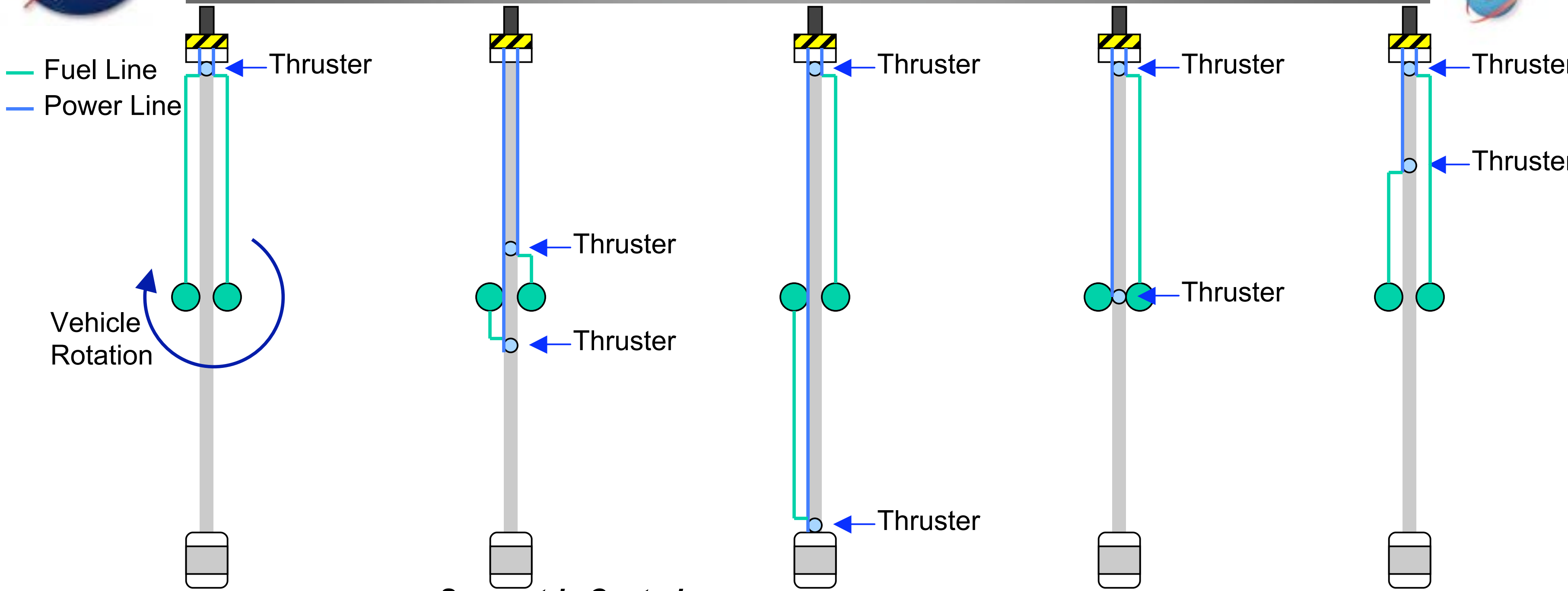
Moment arm = 10 m
Throttle "doublet" applied every 180°
Pulse "Width" = 90° of arc (90% thrusting efficiency)
EP Thruster Eff. = 60%, Nominal Isp = 4000 s
Constant EP Power = 6 MWe
Vehicle I_{xx} =2.1x10^{8} kg-m^{2}







NEP Thruster Location Trades

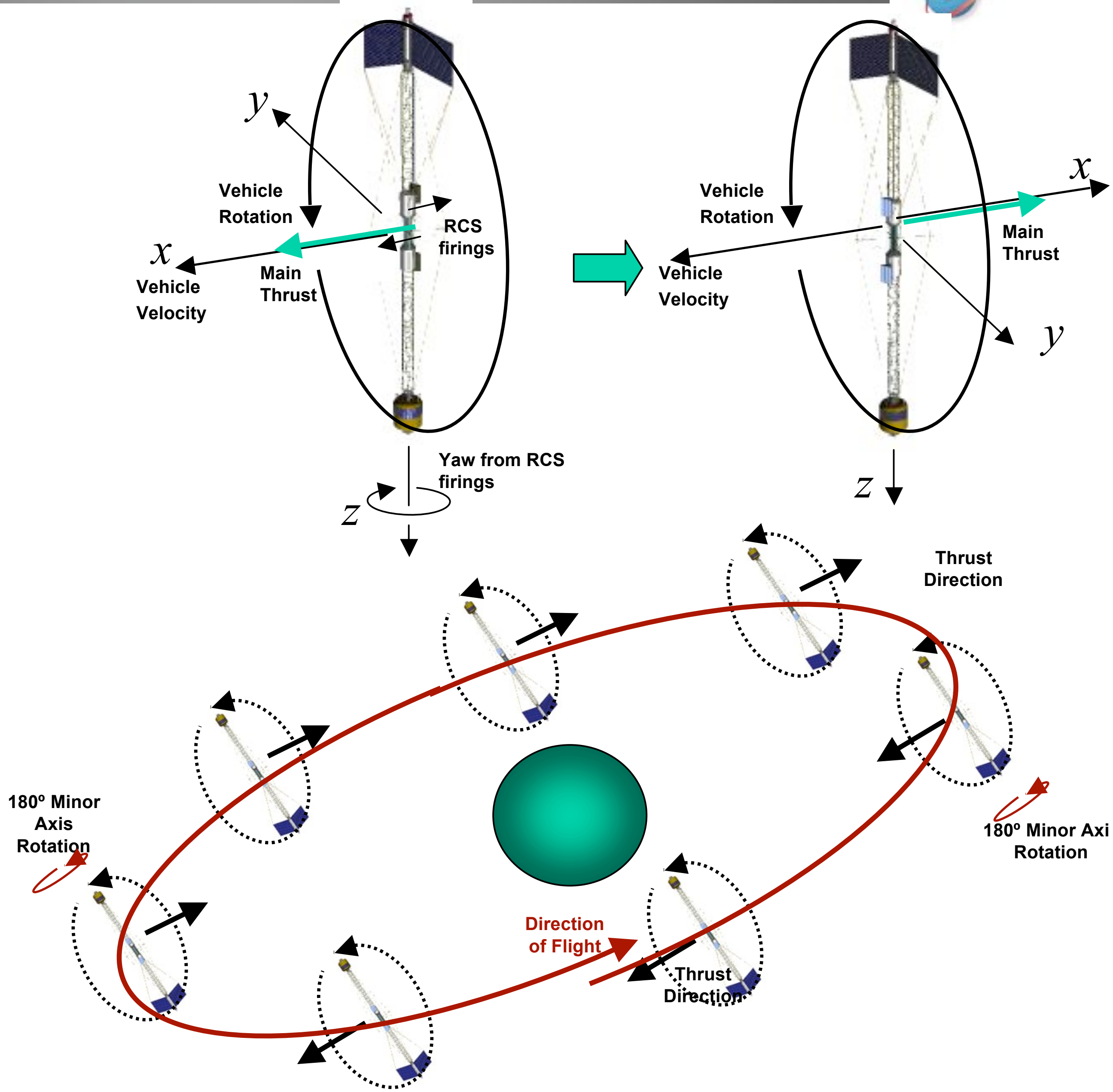


	Original Asymmetric	***Symmetric Central (Selected Config.)***	Symmetric Terminal	Asymmetric CG	Asymmetric Counter
Power Level*	-- High Power Variation	+ Counter-cycling (near constant power)	+ Counter-cycling (near constant power)	+ Counter-cycling (near constant power)	+ Counter-cycling (near constant power)
Power Lines	+ Short power lines	-- Long power lines	-- Long power lines (no worse than prevoius)	-- Long power lines	+ Short power lines
Prop Lines	-- Long prop lines	+ Short prop lines	-- Long prop lines	-- Long prop lines	-- Long prop lines
Turn Rates	+ Higher turn rates	-- Lower turn rates	+ Best turn rates	+ Higher turn rates	-- Lower turn rates

*For constant mass flow rate approach

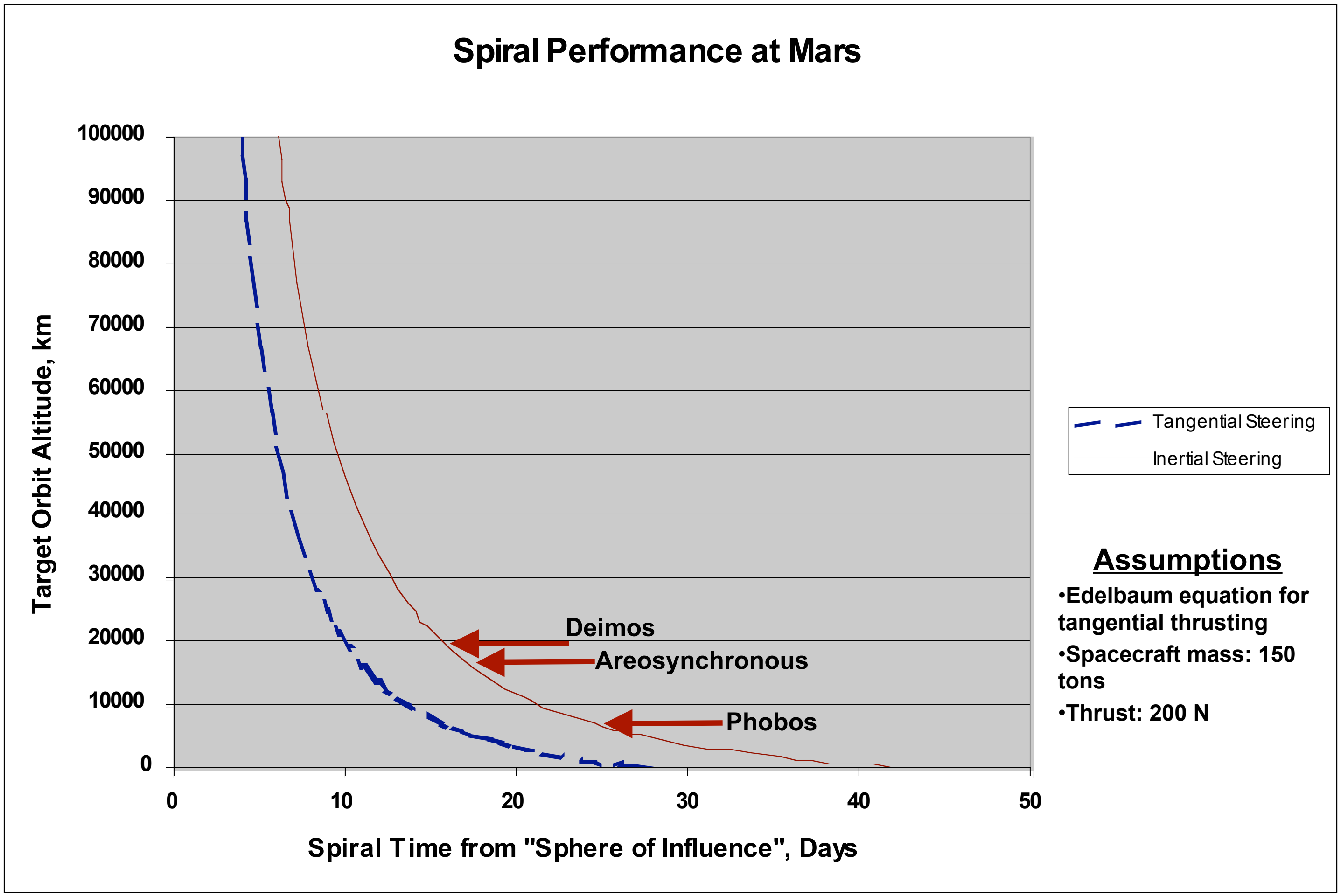
Minor Axis Rotation

- Technique for rotating thrust vector 180°
- Rotation about vehicle z-axis
- Applications:
  - Midcourse turnaround
  - Planetary spirals (if required)
    - ~36% loss of propulsive efficiency vs. tangential thrusting
- Other possible implementation: second set of thrusters (-x thrust direction)
  - Thruster mass/expense vs. propellant required for rotation



Minor Axis Rotation (cont.)

- Spiral efficiency
  - 2/$ efficiency factor (~64%) compared to purely tangential thrusting
- Planetary spiral application (Mars):



Steering Strategy Comparison

Mission Phase	Maximum Turn Required	Maximum Required Turning Rate	Impulse Steering Only (ArcJet)	Impulse + Minor Axis Rotation	Impulse + MAR + Main Propulsion Modulation
Earth-Moon L_1 Departure	180°	15°/day	620 kg	620 kg	537 kg
Heliocentric Outbound, 1st arc	65°	2°/day	224 kg	224 kg	0
Mid-Course Thrust Reversal	180°	~10°/day	620 kg	TBD (small)	TBD (small)
Heliocentric Outbound, 2st arc	65°	2°/day	224 kg	224 kg	0
Mars-Sun L_1 Arrival	small	small	~0	~0	~0
Spiral to/from HMO	Multiple revs	288°/day slew (Deimos) 180°/hr MAR	Impractical	TBD (small)	TBD (small)
Mars-Sun L_1 Departure	180°	2°/day	620 kg	TBD (small)	~0
Heliocentric Inbound, 1st arc	225°	2°/day	775 kg	775 kg	0
Mid-Course Thrust Reversal	180°	~10°/day	620 kg	TBD (small)	TBD (small)
Heliocentric Inbound, 2st arc	225°	2°/day	775 kg	775 kg	0
Earth-Moon L_1 Arrival	180°	15°/day	620 kg	620 kg	537 kg
			5098 kg	**3238 kg**	**1074 kg**

Agenda

- Introduction
- Study Results to Date
  - Trajectory Analysis
  - Dynamics
  - Structures
  - Power, Propulsion
  - Habitation
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Structure

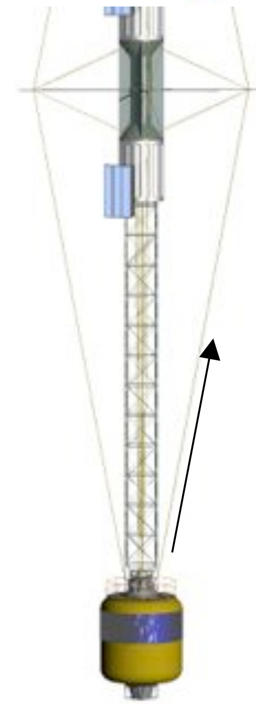
- Extended structure required for 1-g / 4 rpm operation
  - Lightweight (performance)
  - Stiff/Strong ("rigid body" transfer of forces/moments)
  - Deployable (practical assembly)
- "Suspension-Compression" Structure used for "Existence Proof"
  - Allows material optimization for specific load paths (mass minimization)

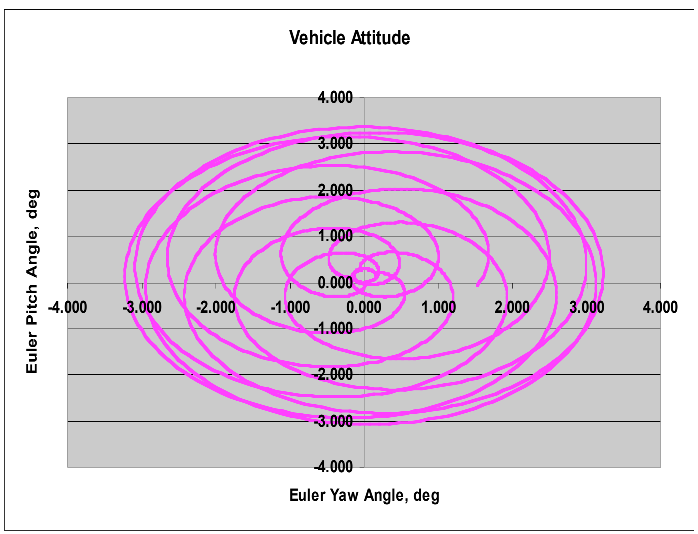
“Suspension-Compression” Structure

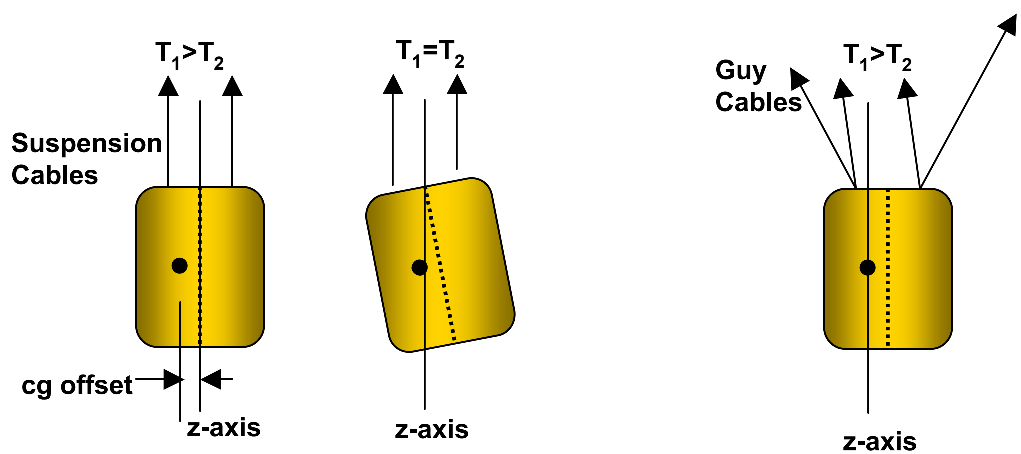
- **Suspension Components**
  - **Suspension Cables**
    - **Counterweight mass support during spin**
  - **Guy cables**
    - **Moment transfer from RCS**
      - **Spinup/spindown**
      - **Steering during spin**
    - **Mass balancing**
  - **“Liquid Crystal Polymer” (LCP) fibers selected for concept vehicle**
    - **Properties used for analysis - Celanese Vectran®**
    - **Excellent tensile properties (Specific Tensile Strength >15x steel)**
    - **Much higher resistance to abrasion, fatigue, UV and radiation than Aramids (i.e. Kevlar®), much lower creep than UHWPE’s (i.e. Spectra®)**
- **Compression Components**
  - **Masts**
    - **Positional control of elements (despun) TBD**
    - **Compression during initial spinup**
    - **Support for power cabling**
    - **Minor axis torques TBD**
  - **Spars**
    - **Guy cable support**
  - **“Ultra High Modulus Graphite” selected for concept vehicle**
    - **Properties used for analysis – BP Amoco Thornel® Carbon Fiber P-650/42 and P-120 Carbon Fiber/Epoxy**
    - **P-120 allows extreme stiffness (Specific Stiffness >9x steel, Al)**
    - **P-650/42 provides very large compressive strength (1720 Mpa Yield)**
    - **Negligible thermal expansion**

Center of Gravity Control

- CG offsets in hab and power modules can cause stability concerns
- Several cg control modes possible
  - Active ballasting/mass trim
    - Disadvantage: ballast & mechanism mass
  - I_{yy} augmentation
    - Disadvantage: ballast mass, decreased maneuverability (esp. minor axis rotation)
  - Active control of suspension/guy cable tension
    - Advantages:
      - Shares load paths with RCS
      - Low mass augmentation for increased loads
- Example – 10% (0.4 m) hab xy-cg misalignment (should be <u>extreme</u> case)
  - 0.4 m cg shift within suspension cable envelope in current design (cables @ 1.3 m)
  - Causes vehicle nutation (“coning”) of ~3°
  - Equalizing suspension cable tension will allow hab rotation & cg alignment – but results in floor tilt (4° for 10% x-cg)
  - Hab guy cables can be utilized for cg alignment while maintaining level

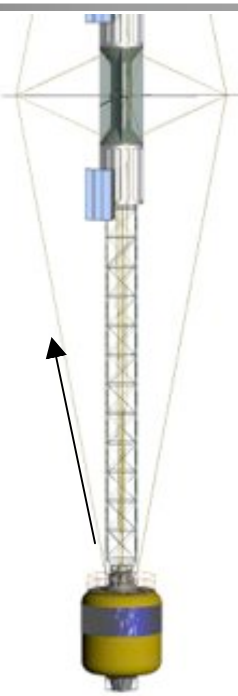


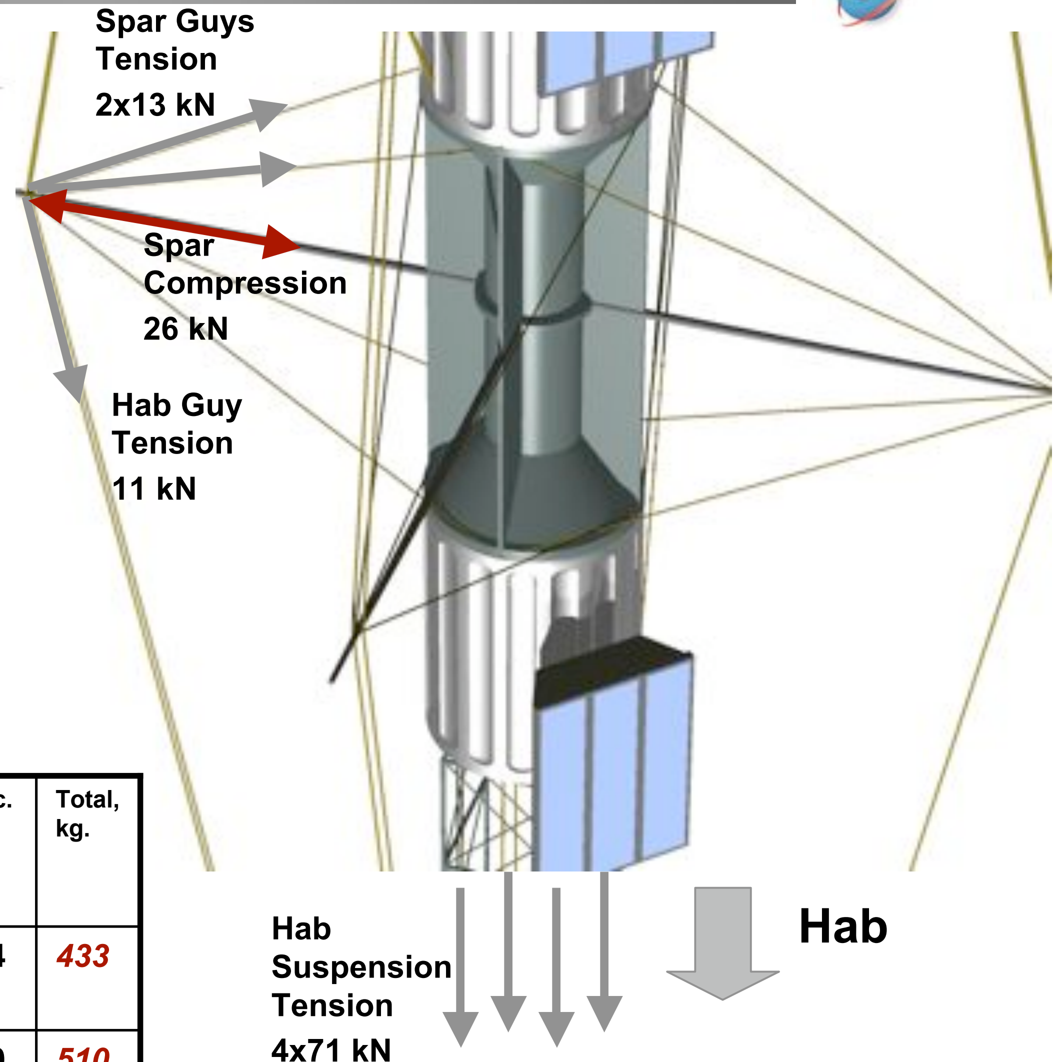




Example Load Paths

- Load paths for 10% hab cg offset
- Assumptions
  - FOS = 5 for cables (Vectran zero creep)
  - Cables doubled for MM failure
  - Misc. includes coatings, spar MM protection, fasteners, etc.)
- Loads for RCS torques will be two orders of magnitude smaller





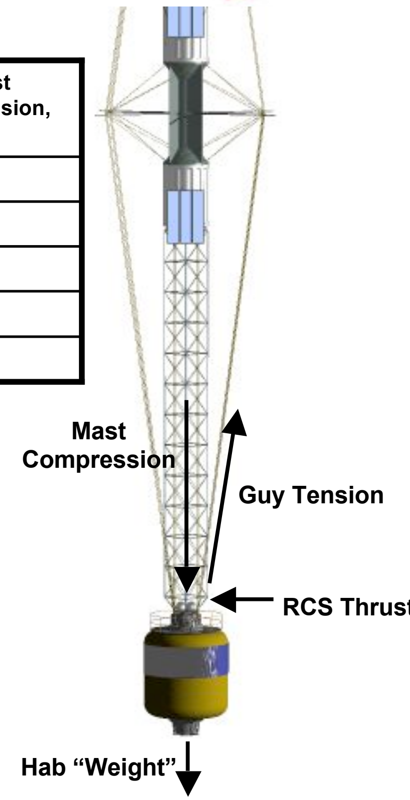
C.G. Offset	Suspension Cables, kg.	Hab/Reactor Guy Cables, kg.	Spar Guy Cables, kg	Spars, kg	Misc.	Total, kg.
5%	148	11	6	124	144	*433*
10%	148	22	12	158	170	*510*
15%	148	33	19	182	191	*573*

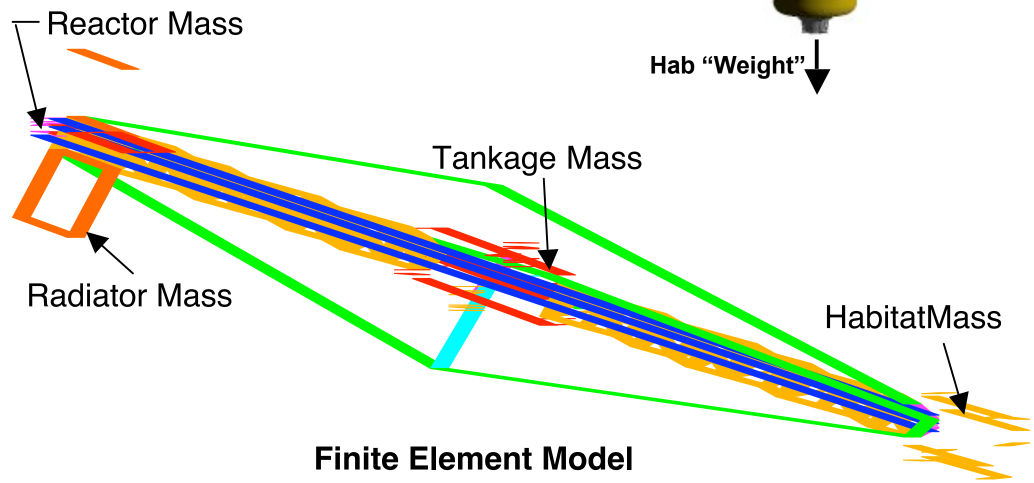
Example Load Paths (cont)

- Mast loads for spinup, spindown
  - Mast will be under compression only during period when Hab Module/Power Module "weight" is less than compression load
    - Only mast loads identified to date
  - After that, no load (suspension cables support loads)
  - For spinup/down times less greater than 24 hours, compression loads will not exceed 100N (22 lbs)
  - Maximum mast loads may result from <u>zero-g</u> operations (hard to quantify at this time)
    - Docking forces
    - Plume impingements
- LaRC Analysis
  - Providing finite element modeling and analysis for load conditions
    - 1-g
    - Spinu/spindown
    - Maneuvers during transit
  - From loads analysis, determine low lightweight a structure (such as inflatabe/rigidizable structures) could be used for mast
  - Status
    - Modeling nearly complete
    - Analysis to begin shortly

Thrust Level, N	Spinup Time, hrs.	ArcJet Power, kWe	Guy Tension, N	Max. Mast Compression, N
5	100	65	24	23
10	50	131	47	46
15	33	196	71	70
20	25	262	95	93
25	20	327	119	116

ArcJet Computations Assume:
Efficiency 30%
Isp 800 sec





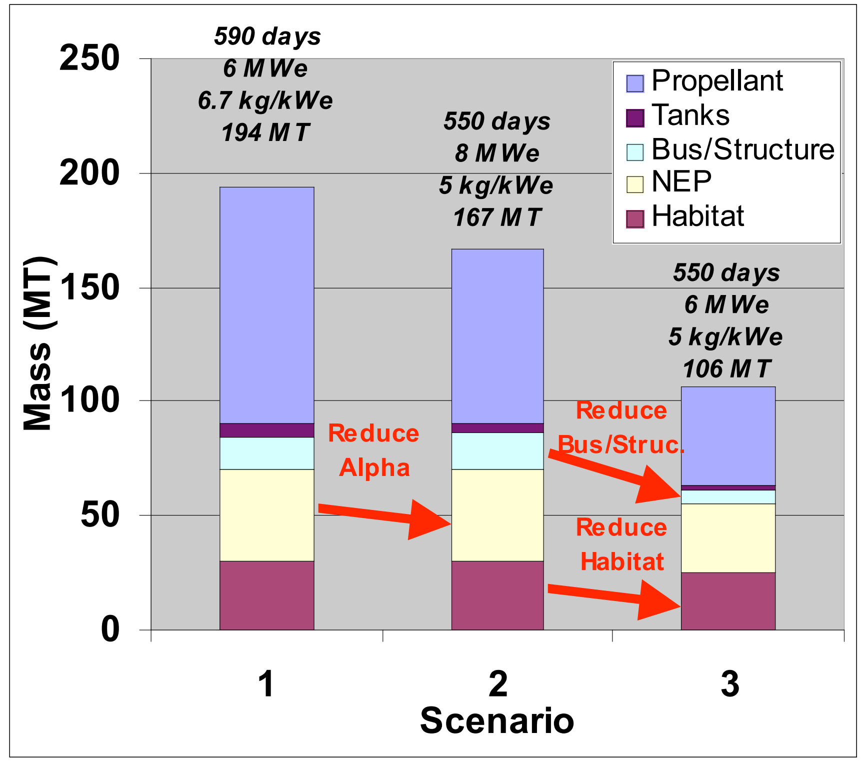
Finite Element Model

Agenda

- Introduction
- <u>Study Results to Date</u>
  - Trajectory Analysis
  - Dynamics
  - Structures
  - <u>Power, Propulsion</u>
  - Habitation
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Three Point Scenarios

Mission Time (days):	**590**	**550**	**550**
Power (MWe):	**6**	**8**	**6**
Specific Impulse (sec):	**4675**	**5970**	**6944**
Alpha Goals (kg/kWe):	**6.7**	**5**	**5**
Nuclear Power	5	3.8	4.2
EP/PPU/PMAD	1.7	1.2	0.8
Initial Vehicle Wet Mass:	**193.8**	**167**	**106.4**
Propellant Mass:	*103.8*	*77*	*43.2*
Dry Vehicle Mass:	*90*	*90*	*63.2*
Payload	30	30	25
NEP	40	40	30
Nuclear Power	30	30	25
EP/PMAD	10	10	5
Bus/Structure	14.8	16.2	6
Boom/Struts/Cables	2	2	
Core Module	5	5	
Wet RCS	4	4	
TBD	3.8	5.2	
Tanks	5.2	3.85	2.2

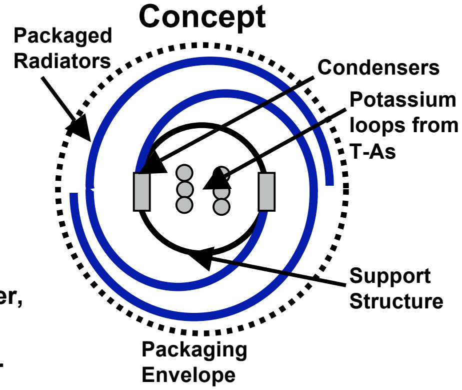


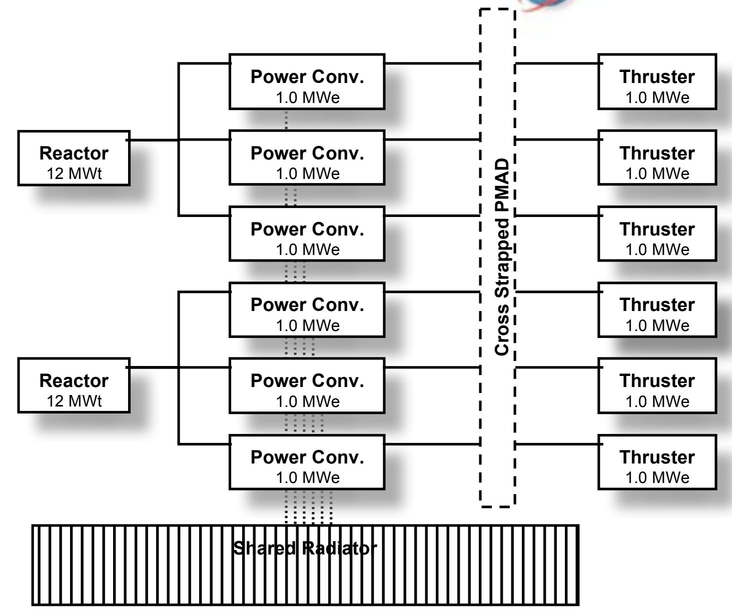
- **Three technology sets scoped w/ varied NEP, habitat, and bus mass goals**
- **All meet ~1.5 year total mission duration goals in 2018 opportunity**
- **Wet mass ranges from 100 to 200 MT**
- **7 kg/kWe consistent w/ SEI projections of scaled SP-100 reactor + 1400K Rankine***
- **5 kg/kWe consistent w/ SEI projections of advanced reactor + 1500K Rankine***
- **Trajectory analysis courtesy NASA/GRC**
- *** Reference: AIAA 91-3607, “Multimegawatt Nuclear Power Systems for NEP”, J. A. George.**

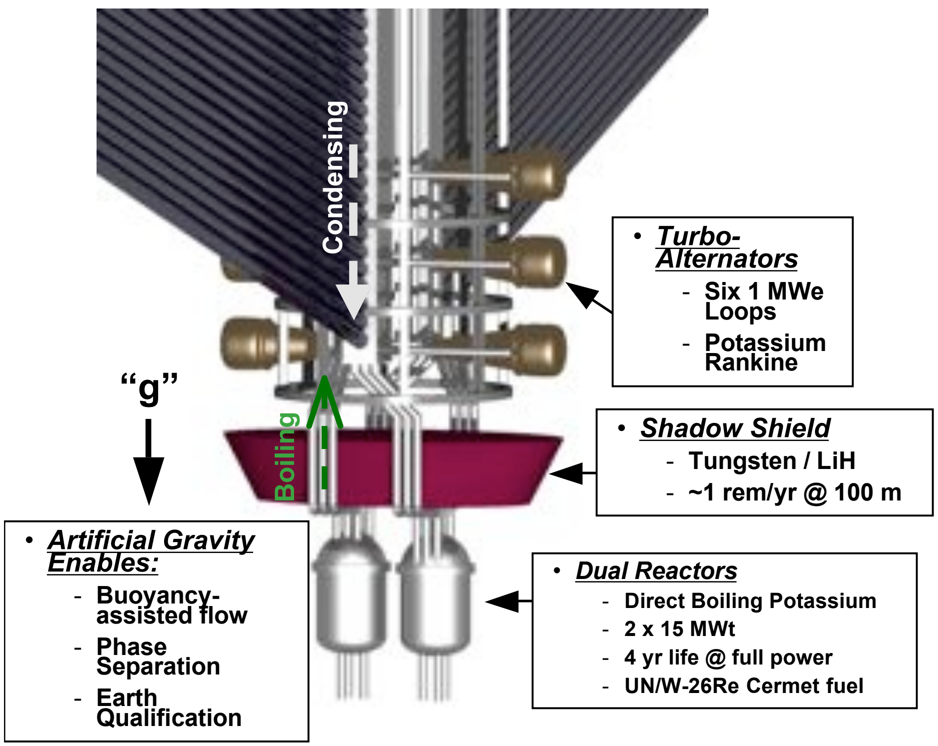
Power Module Concept

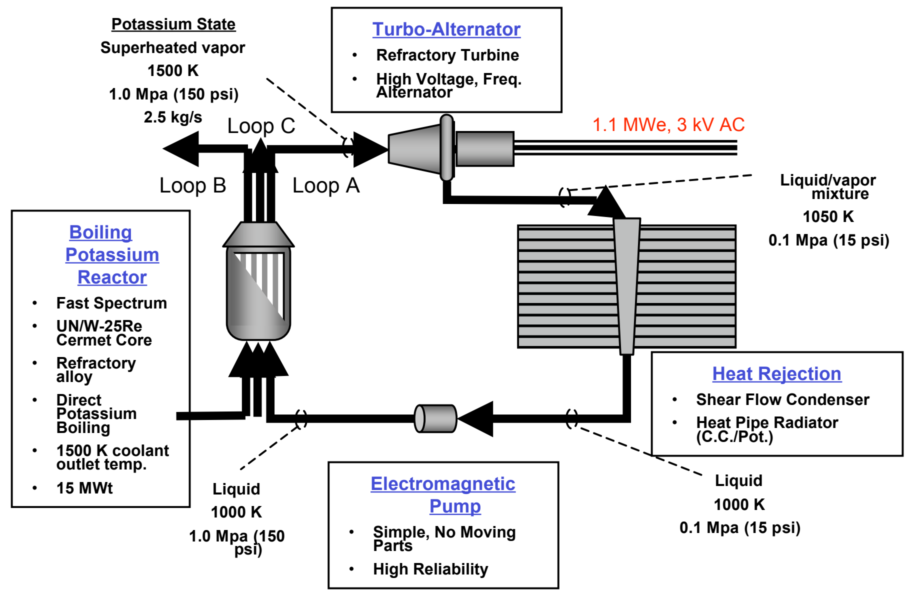
- Rankine Conversion assumed due to:
  - Lowest mass @ MWe powers
  - *Lowest radiator area*
  - Lowest reactor temperature
  - Though adds complexities of 2-phase fluid mgmt. & liq. metals (thaw, handling)
- Primary radiator (~500-700 m^2, ~1000K) assumes technologies under previous development for advanced SP-100 radiators (reference Al Juhasz, NASA/GRC).
  - C-C composite heat pipe radiators, metal liner, potassium working fluid (5 kg/m^2).
  - Flexible woven "fabric" radiators (DOE/PNL).
- A potential deployment scheme has been identified .

Radiator Packaging Concept



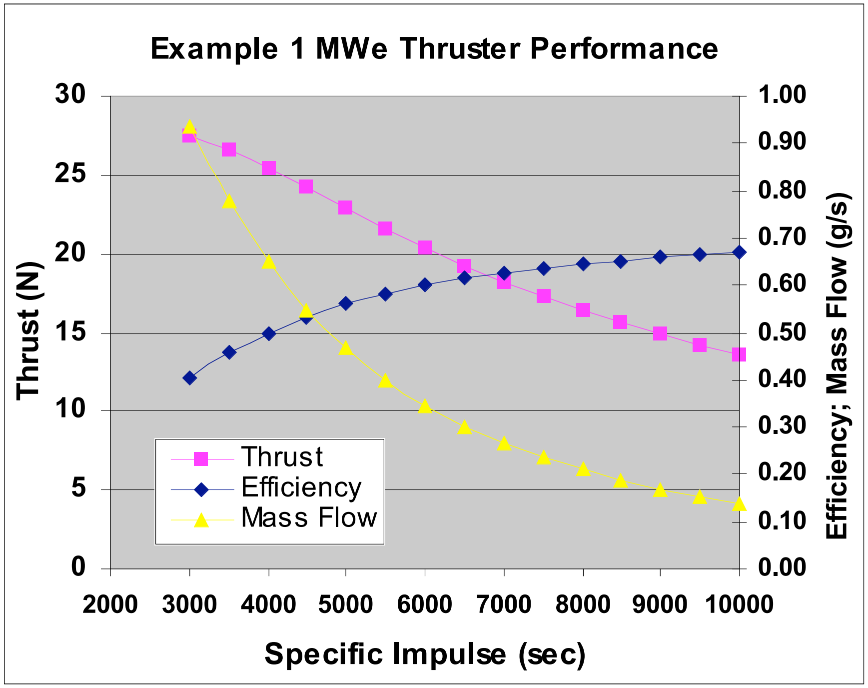




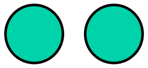


Electric Propulsion Options

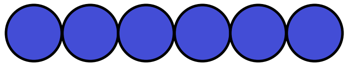
- Ion, MPD, and VASIMR thruster technologies appear most promising for scalability to high power
- <u>Ion Thrusters</u>
  - Pros: Operational @ low power, propellant properties
  - Cons: Grid scaling
- <u>MPD Thrusters</u>
  - Pros: Demo'd @ 100's kWe, compact
  - Cons: Lifetime, Li issues
- <u>VASIMR</u>
  - Pros: Lifetime, scaling
  - Cons: Low maturity, propellant properties
- <u>Propellant Properties:</u>
  - Argon: 1400 kg/m^3, 87 K (liquid)
  - Lithium: 500 kg/m^3
  - Deuterium: 170 kg/m^3, 23 K (liquid)



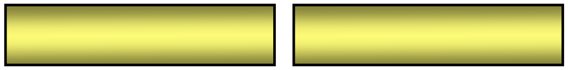
<u>Ion Argon Tanks:</u>
100 MT design load
2 spheres @ 4.1 m ID, 4.3 m OD



<u>MPD Lithium Tanks:</u>
100 MT design load
6 spheres @ 4.0 m ID, 4.2 m OD



<u>Vasimr Deuterium Tanks:</u>
100 MT design load
2 cylinders ~ 4.5 m Dia, 20 m long



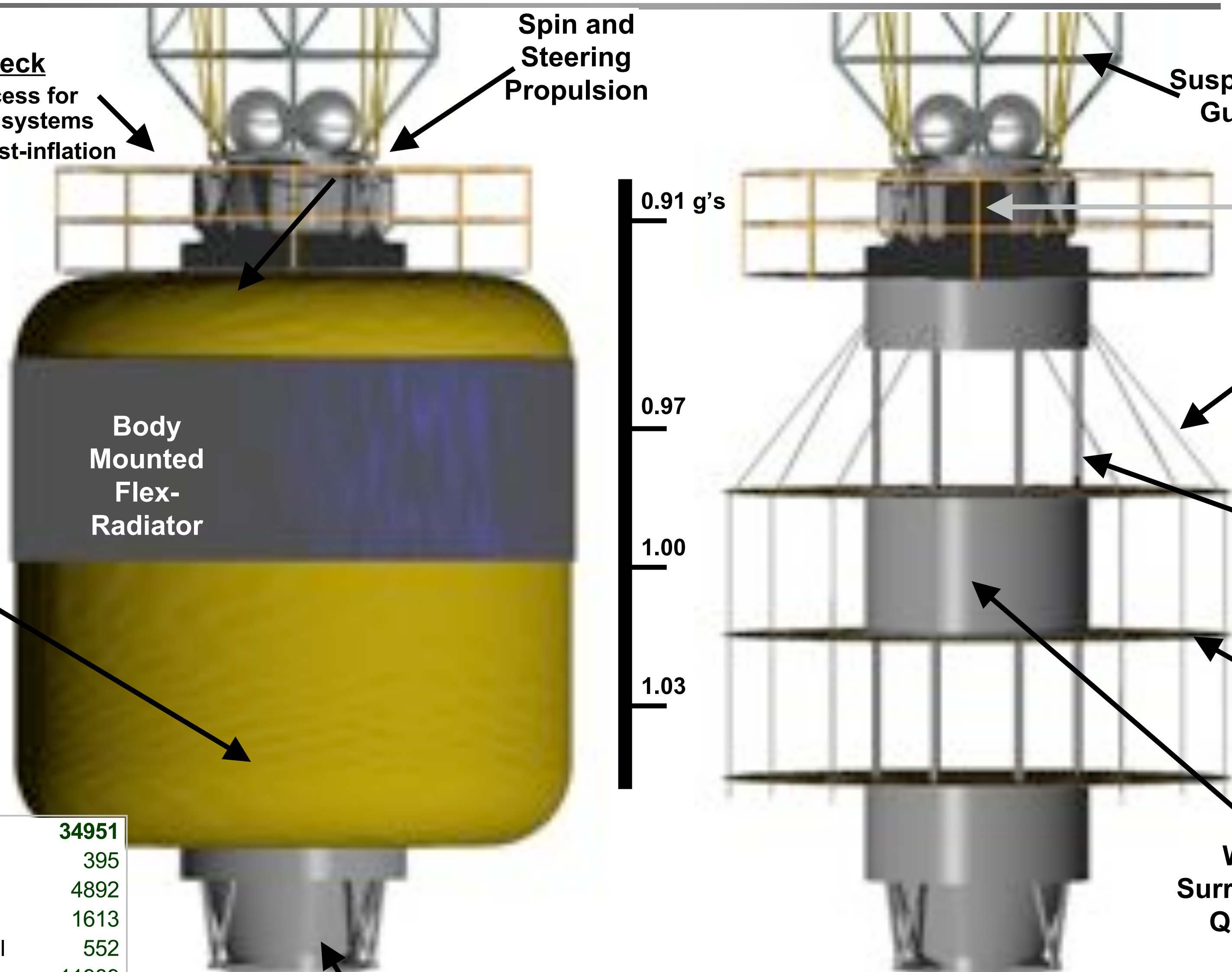
Agenda

- Introduction
- <u>Study Results to Date</u>
  - Trajectory Analysis
  - Dynamics
  - Structures
  - Power, Propulsion
  - <u>Habitation</u>
  - Configuration/Other Systems
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Crew Module Concept

EVA Deck

- Provides access for external hab systems
- Deployed post-inflation



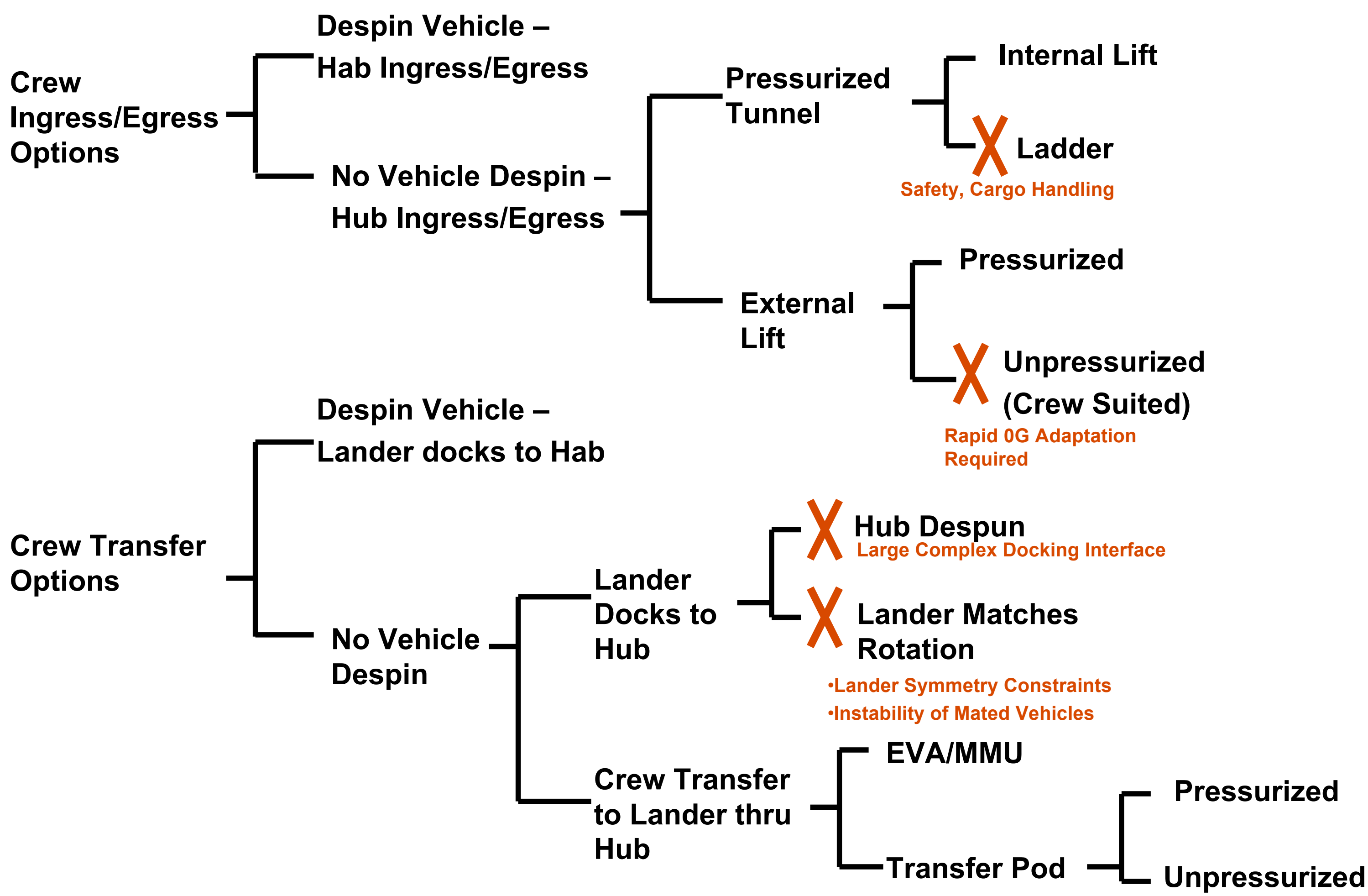
Habitat	**34951**
Avionics	395
ECLS	4892
EVA	1613
Thermal Control	552
Human Factors	11989
Medical Ops	1048
Structures	12957
Power	1505

Agenda

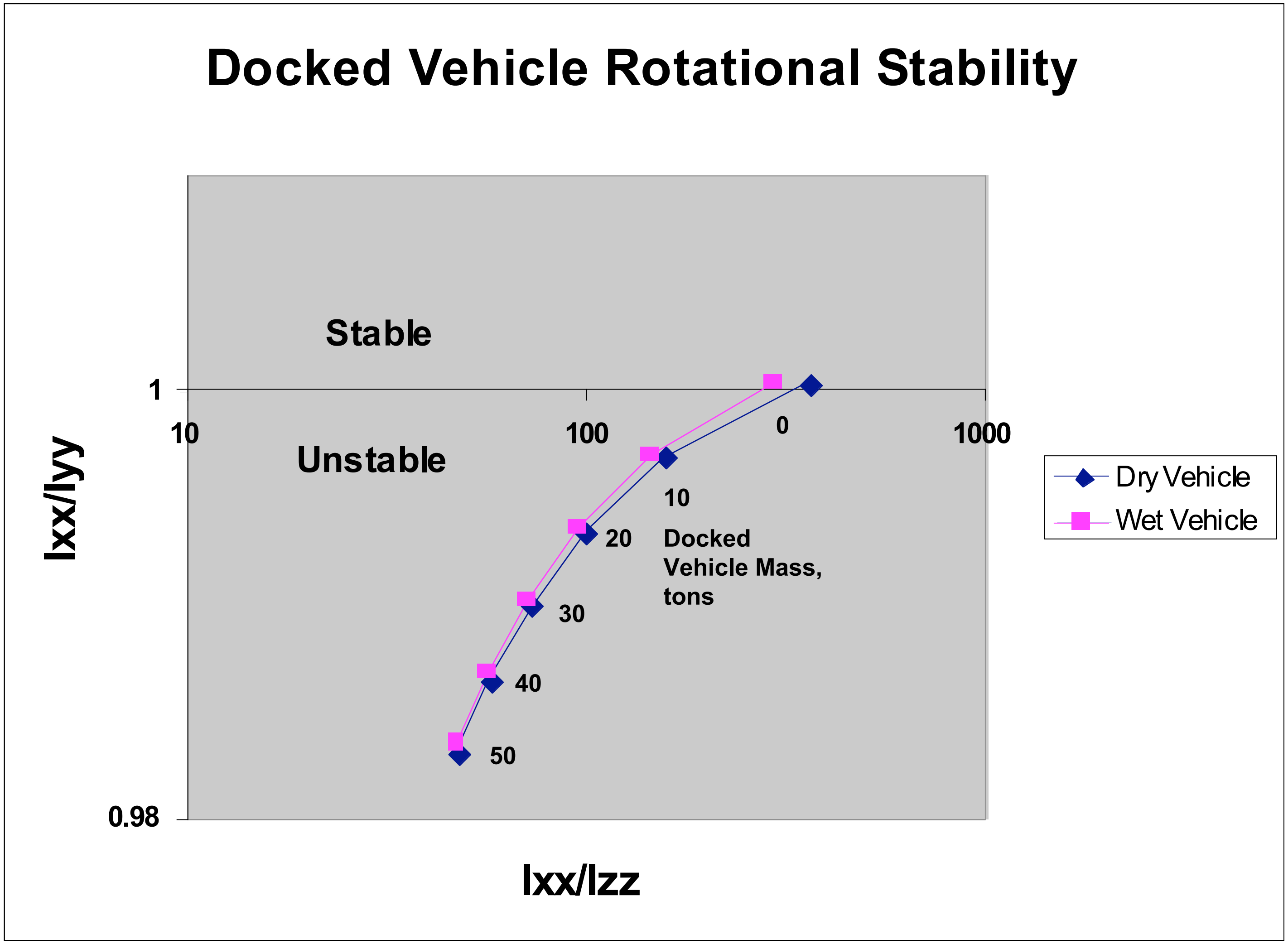
- Introduction
- <u>Study Results to Date</u>
  - Trajectory Analysis
  - Dynamics
  - Structures
  - Power, Propulsion
  - Habitation
  - <u>Configuration/Other Systems</u>
  - Architecture Issues
- Conclusions Drawn (so far)
- Future Work

Crew/Cargo Ingress/Egress

- Assumption: During major assembly/refit operations, vehicle is despun
  - Hab outfitting
  - Fluids/propellant/consumables loading
- Ingress/egress options during mission still being investigated



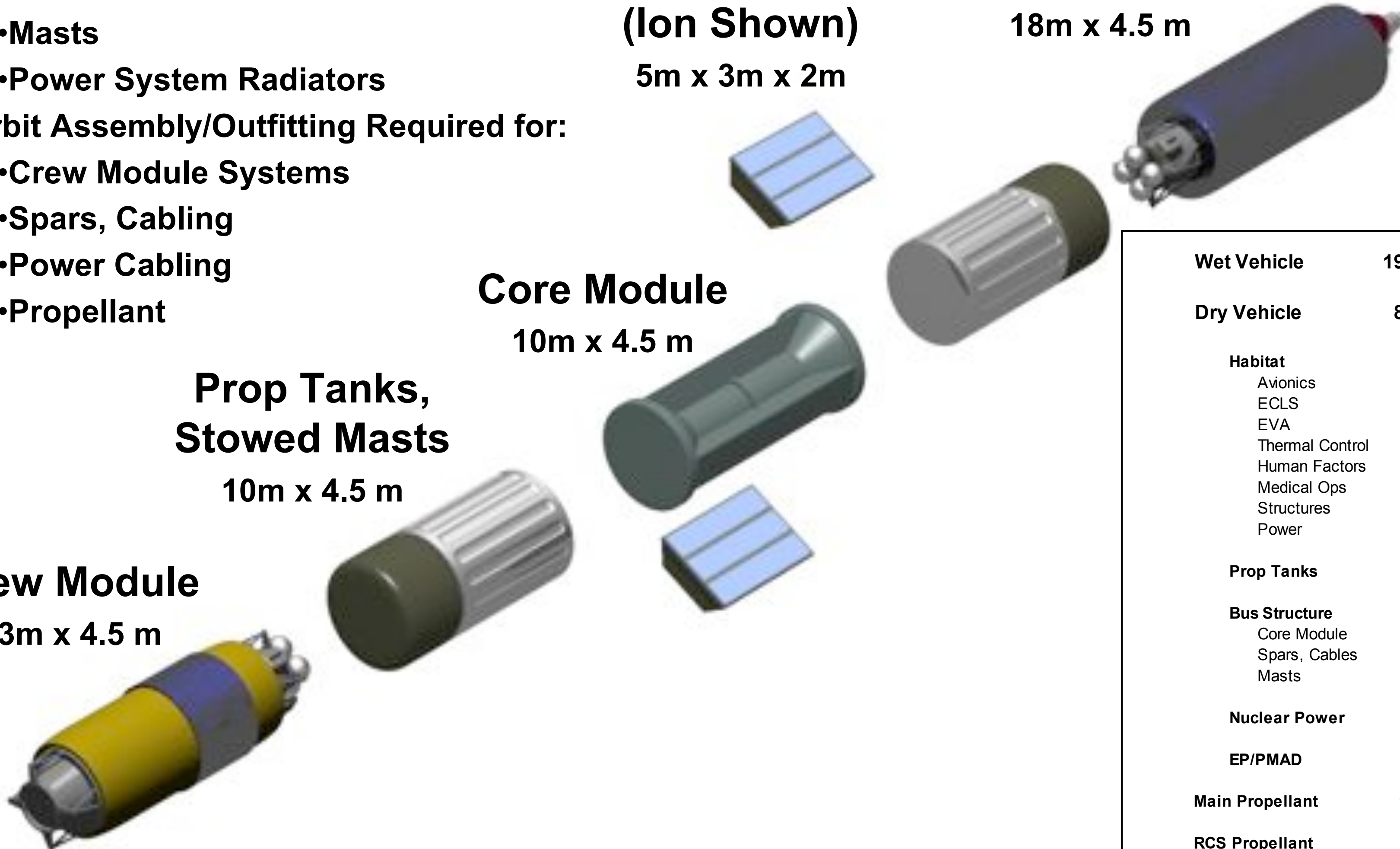
Hub Docking Destabilization



Mass Breakout & Preliminary Launch Packaging

On-orbit Deployment:
- Crew Module Inflation
- Masts
- Power System Radiators

On-orbit Assembly/Outfitting Required for:
- Crew Module Systems
- Spars, Cabling
- Power Cabling
- Propellant



Wet Vehicle	**194961**
Dry Vehicle	**87161**
Habitat	**34951**
Avionics	395
ECLS	4892
EVA	1613
Thermal Control	552
Human Factors	11989
Medical Ops	1048
Structures	12957
Power	1505
Prop Tanks	**5200**
Bus Structure	**7010**
Core Module	5000
Spars, Cables	510
Masts	1500
Nuclear Power	**30000**
EP/PMAD	**10000**
Main Propellant	**103800**
RCS Propellant	**4000**

Green - Bottoms-up or high confidence estimate
Orange - SWAG
Red - WAG

Agenda

- Introduction
- <u>Study Results to Date</u>
  - Trajectory Analysis
  - Dynamics
  - Structures
  - Power, Propulsion
  - Habitation
  - Configuration/Other Systems
  - <u>Architecture Issues</u>
- Conclusions Drawn (so far)
- Future Work

Architecture Issues to be Addressed

- **Initial transport from LEO to EM L_1**
  - Assembly location
  - Initial transport to L_1
  - Consistency with "Earth's Neighborhood" infrastructure
- **Refurbish/refuel at L_1**
  - Required infrastructure
  - Transport of consumables to L_1
- **Destinations**
  - If low planetary orbit is destination, different mission archetype and/or vehicle configuration may serve better
  - Config. 2 provides faster, more efficient spiral down/up
  - Much of Mars stay-time (3 mo.) would be spent in spiral down/up

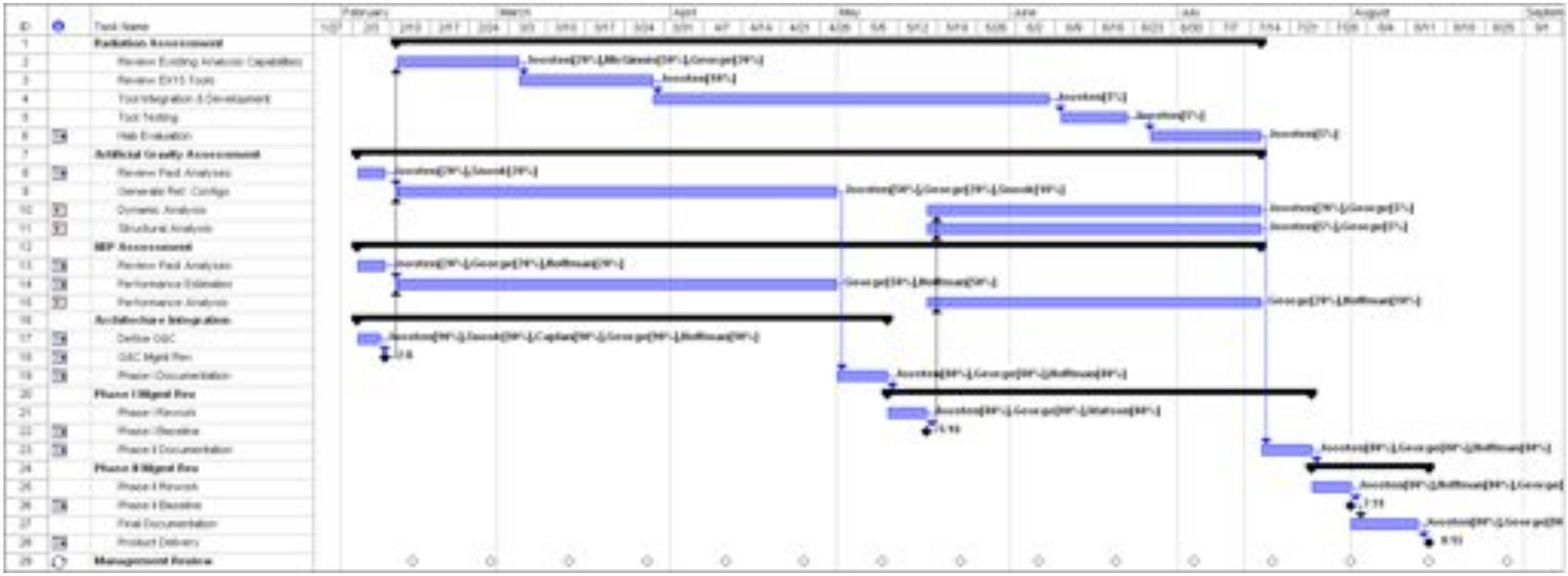
Conclusions Drawn (so far)

- Archetype mission requirements met
  - Transit time reduction, perihelion increase may be possible
    - Additional thrust arcs
    - Increased power levels, more aggressive specific power technology
    - Venus gravity assist
- Major challenge unique to Config. 1 addressed
  - Steering strategies identified consistent with archetype mission requirements
  - Propellant requirements not excessive
  - Small effects of mass imbalances – control strategies identified
- AG may provide significant advantage for system test & certification
  - Long-duration zero-g testing not required
    - Environmental control and life support
    - Power conversion

Conclusions Drawn (so far)

- **Config. 1 mass penalties associated with AG appear minimal**
  - **Separation distances associated with nuclear system used advantageously (validates choice of NEP)**
  - **No massive despun joints, interfaces, etc. (hub ingress/egress TBD)**
  - **Good convergence between power system mass as habitat counterweight and propulsive performance *utilizing reasonable specific power and thruster performance***
  - **Tension/compression structures appear to be very mass efficient**
    - **Boom design and mass TBD**
  - **Multiple spinup/spindown sequences appear unnecessary (crew ingress/egress TBD)**
  - **Steering while under spin does not require large propellant quantities**
    - **Virtually “free” in heliocentric space**
- **Vehicle Assembly**
  - **Attempt was made to maintain module envelope: 5m x 18m x 35 mt**
  - **Consistent with “Earth’s Neighborhood” architecture requirements (augmented Delta IV Heavy)**
- **Challenging 90-day stay Mars mission appears achievable**
  - **18-24 month round trip and *no crew g-adaptation time* at Mars**
  - **Transit vehicle mass of 200 tons or less**

Schedule & Future Work



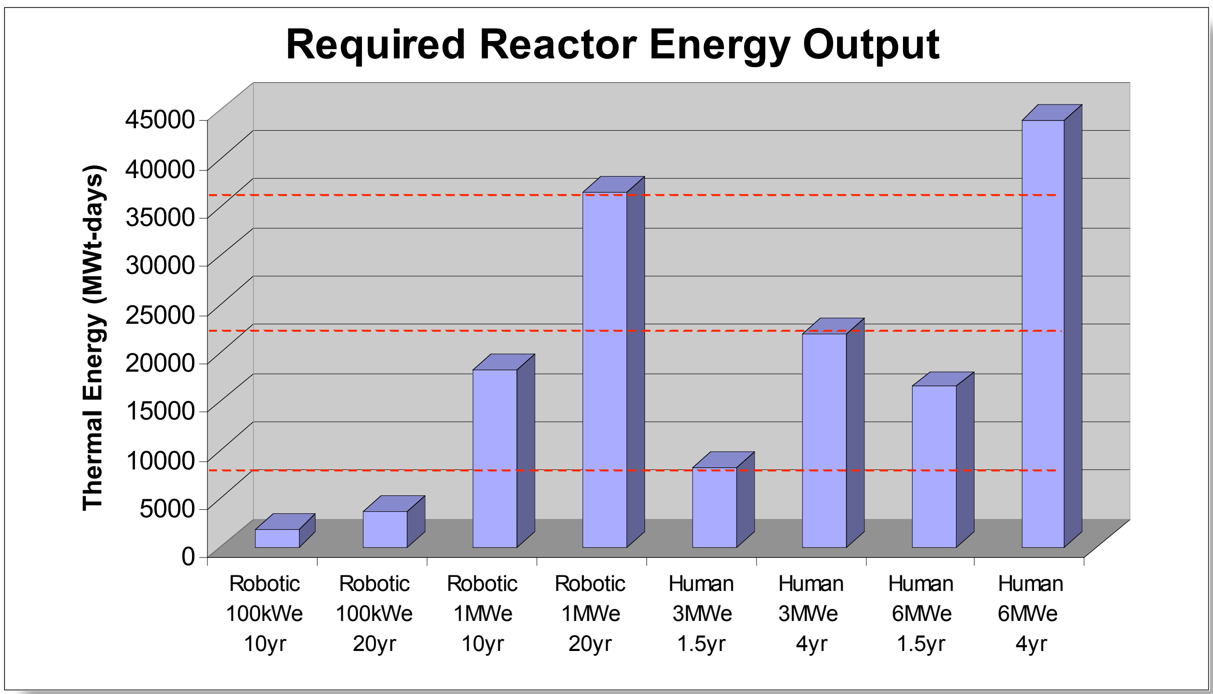
- **Targeted contracted study**
  - **Structural analysis, mast deployment concepts – AEC Able**
- **Additional studies**
  - **Refine launch packaging**
  - **Crew ingress/egress concepts & recommendation**
  - **Micrometeorite environment & shielding strategies**
  - **Habitat radiation shielding assessment**
- **Potential additional studies**
  - **Reactor radiation scattering**
  - **Definition on deployable high-temp radiator**

Backup

Reactor Energy Requirements

- **A "middle ground" may exist between human and robotic energy needs**
  - **Robotic NEP: 100's kWe for 10-20 yr**
  - **Human NEP: few MWe's for 2-4 yr**
  - **A reactor capable of ~10,000-20,000 MWt-days, w/ sufficient throttleability, may be capable of serving both needs**

Mission	Electrical Power (MWe)	Thermal Power (MWt)	Duration (years)	Duration (days)	Energy from Rx (MWt-days)
Robotic 100kW	0.1	0.5	10	3653	1826
Robotic 100kW	0.1	0.5	20	7305	3653
Robotic 1MWe	1	5	10	3653	18263
Robotic 1MWe	1	5	20	7305	36525
Human 3MWe	3	15	1.5	548	8218
Human 3MWe	3	15	4	1461	21915
Human 6MWe	6	30	1.5	548	16436
Human 6MWe	6	30	4	1461	43830



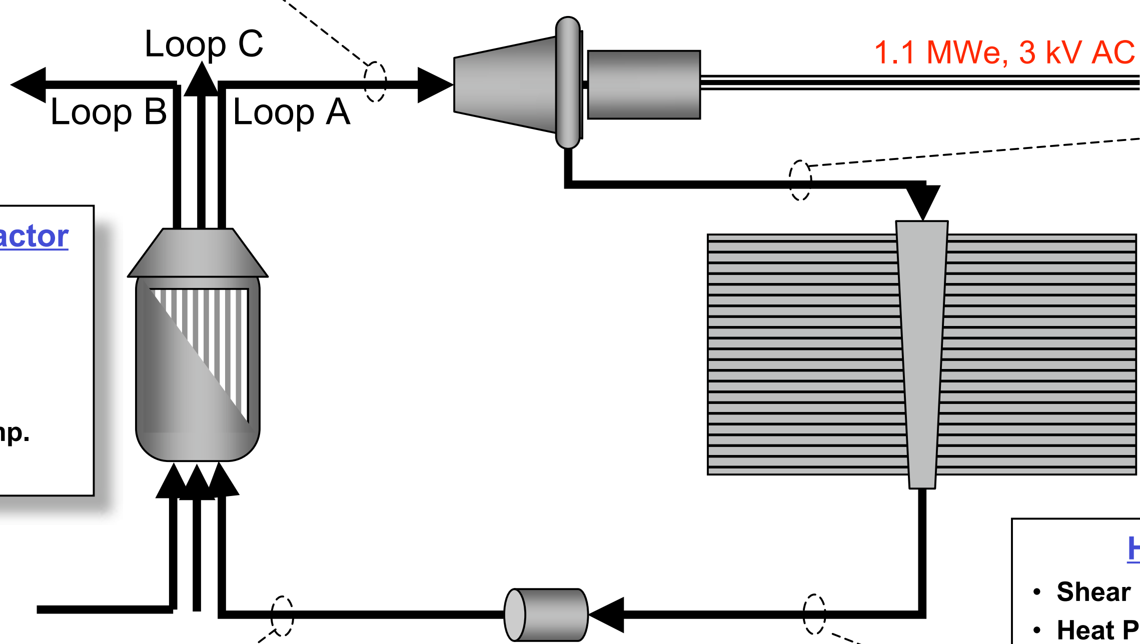
A Megawatt-class Nuclear Power Concept

(Simplified Schematic)

Module Power = 3 MWe (3 loops)
Full Power Life = 4 yr
Est. Specific Mass = 3-4 kg/kWe
(Estimated by analogy with past SEI and industry concepts; no PMAD or EP incl.)

Potassium State
Superheated vapor
1500 K
1.0 Mpa (150 psi)
2.5 kg/s

Turbo-Alternator
- Refractory Turbine
- High Voltage, Freq. Alternator



Liquid/vapor mixture
1050 K
0.1 Mpa (15 psi)

Boiling Potassium Reactor
- Fast Spectrum
- UN/W-25Re Cermet Core
- Refractory alloy
- Direct Potassium Boiling
- 1500 K coolant outlet temp.
- 15 MWt

Heat Rejection
- Shear Flow Condenser
- Heat Pipe Radiator (C.C./Pot.)

Liquid
1000 K
1.0 Mpa (150 psi)

Electromagnetic Pump
- Simple, No Moving Parts
- High Reliability

Liquid
1000 K
0.1 Mpa (15 psi)

Observations from past NEP Systems Studies

- **Technology selections not as critical at low powers (10's kWe), but has dramatic impact at high powers (MWe's)**
- **Cycle operating temperatures single most important driver to both:**
  - **System performance (mass, alpha, radiator area)**
  - **Degree of technical difficulty (fuels, materials, etc.)**
- **Fast Spectrum / Liquid Metal Cooled Reactors (LMR) typically smaller & lighter than Gas Cooled Reactors (GCR)**
- **Brayton & Rankine best suited power conversion at multi-megawatts**
- **Brayton:**
  - **Simple, single phase fluid**
  - **Low rejection temperatures → large, more massive radiators**
- **Rankine:**
  - **Adds complexities of 2-phase fluid management, liq. metal handling & thaw**
  - **High rejection temperatures → smaller, lighter radiators & system mass**
- **Rankine systems lighter for same reactor temperature**
- **For stated mass ("alpha") objective, Rankine can be used to "buy down" temperature in reactor fuels, materials, and overall cycle**

Habitation

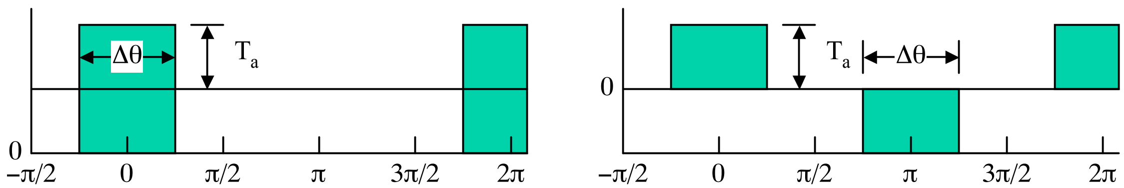
System	Description	Implications of 1-g	Implications of Robust Power	Mass (kg)
Avionics	• Provides command, control, communications, and computation for vehicle operations • Allows voice, data, and video communication to Earth, Mars surface, orbital assets, and EVA crewmembers • Provides an integrated health management system for onboard and ground monitoring	• No major impacts	• Enhanced redundancy for computation and instrumentation • Improved communication and data transmission	395
Environmental Control and Life Support	• Based on a partially closed-loop design (air and water are recycled, solid waste is stored) • Provides a shirtsleeve living environment for the crew	• Enables ground testing of flight hardware • Requires pumps to counteract gravity in fluid systems (~10% or 110 watt pumping power requirement increase)	• Permits the use of lighter, smaller, more capable system components	4892
Extra-Vehicular Activity	• An inflatable airlock will allow two crewmembers to egress per EVA • Advanced lightweight suits will accommodate movement in the 1-g environment	• Requires development of lightweight suits (ie. current 53 kg vs. needed 22 kg on-back carrying mass)	• No major impacts	1613
Thermal Control	• Collects heat from coldplates and heat exchangers which is rejected through body mounted radiators	• Requires pumps to counteract gravity in fluid systems (~10% or 110 watt pumping power requirement increase) • Requires sturdy radiator mounting technique	• Allows heat leaks to be overcome by direct heating rather than adding heavy insulation to shell • Thermal rejection requirements must be met	552

Habitation

System	Description	Implications of 1-g	Implications of Robust Power	Mass (kg)
Human Factors & Habitability	• Provides system hardware, appliances, and food to accommodate a crew of 6 on an 18-month mission • Provides living and working quarters for crewmembers	• Major impact to habitat layout – floor space only • Allows hardware to be modeled after Earth-based counterparts (ie. sinks, showers, ovens, etc…)	• Permits the use of appliances that improve the standard of living (ie. dishwasher, freezers, clothes washer/dryer, etc…)	11989
Medical Operations	• Systems will enable remote monitoring of crewmembers, data acquisition, analysis, and interpretation • Distributed architecture allows access to software from any computer	• Enables standard 1-g protocols to be followed during various procedures (ie. advanced cardiac life support, medication purification, etc…)	• Significant benefits by allowing power-intensive equipment, bioinstrumentation, and telecommunication (ie. x-ray, bone densitometry, virtual reality training, etc…)	1048
Structures & Mechanisms	• Inflatable module based on Transhab design, modified to accommodate loading in a 1-g environment • Outfitting missions will be required • Radiation shielding considerations included	• Requires major modifications to original Transhab design in order to accommodate 1-g loading	• May encourage growth in other systems, thus require greater structural mass	12957
Electrical Power	• Approximately 15 kWe is delivered to the habitat • Fiber Li-Ion batteries perform power conditioning and supply 24 hours of emergency power at 50% nominal load • Power is delivered to system hardware in three forms: 115 Vac 400 Hz; 115 Vac 60 Hz; 28 Vdc	• No major impacts	• Allows increased power requirements to be easily met • May increase wiring and power distribution hardware masses	1505

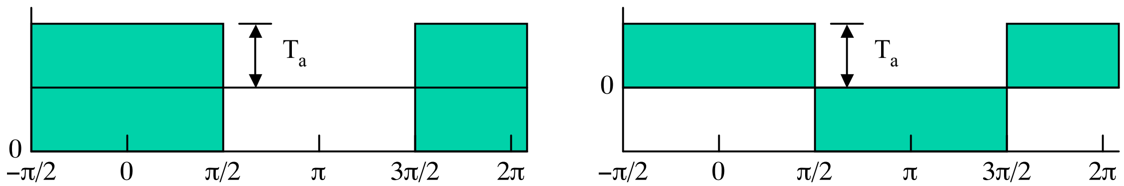
Thrust Profile Factors (f)

Turn rate: $\dot{\psi} = f \dfrac{r\,T_a}{I_{xx}\omega_S}$



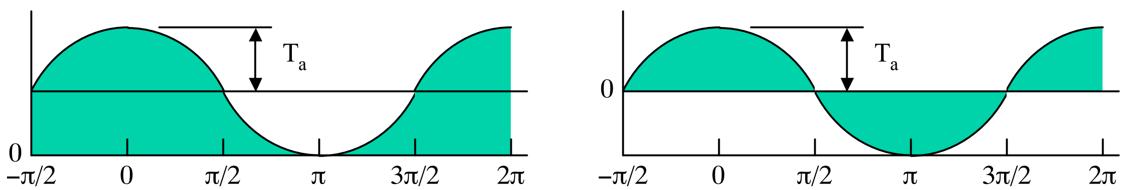
Step function pulse

$$f = \frac{2}{\pi}\sin\frac{\Delta\theta}{2}$$



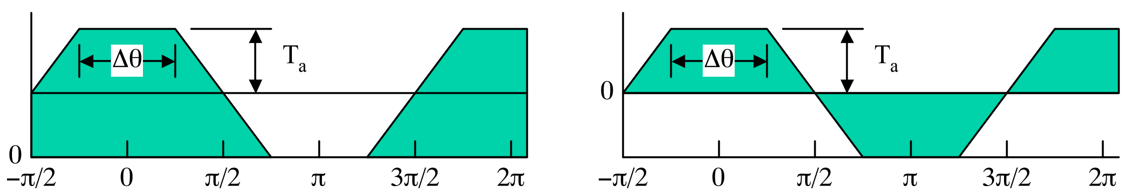
Step function over half arc

$$f = \frac{2}{\pi}$$



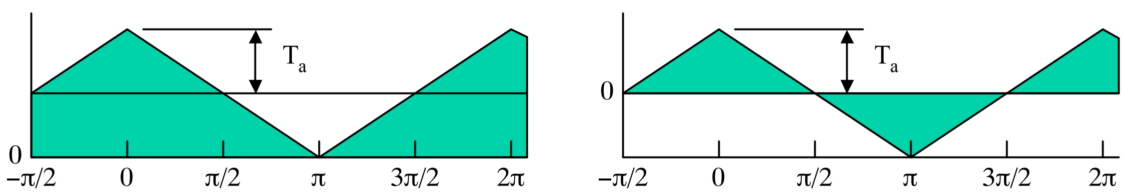
Sinusoid

$$f = \frac{1}{2}$$



Ramp with plateau

$$f = \frac{4}{\pi(\pi - \Delta\theta)}\cos\left(\frac{\Delta\theta}{2}\right)$$



Ramp function

$$f = \frac{4}{\pi^2}$$